BRISTOL BAY RED KING CRAB STOCK ASSESSMENT IN SPRING 2011

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Executive Summary

1. Stock: red king crab (RKC), *Paralithodes camtschaticus,* in Bristol Bay, Alaska.
2. Catches: The domestic RKC fishery began to expand in the late 1960s and peaked in 1980 with a catch of 129.95 million lbs (58,943 t). The catch declined dramatically in the early 1980s and has stayed at low levels during the last two decades. Catches during recent years were among the high catches in last 15 years. The retained catch was about 4 million lbs (1,814 t) less in 2009/10 than in 2008/09. Bycatch from groundfish trawl fisheries were steady and small during the last 10 years.
3. Stock biomass: Estimated mature biomass increased dramatically in the mid 1970s and decreased precipitously in the early 1980s. Estimated mature crab abundance has increased during the last 20 years with mature females being 4.4 times more abundant in 2010 than in 1985 and mature males being 2.8 times more abundant in 2010 than in 1985.
4. Recruitment: Estimated recruitment was high during 1970s and early 1980s and has generally been low since 1985 (1978 year class). During 1985-2010, only estimated recruitment in 1995, 2002 and 2005 was above the historical average for 1969-2010. Estimated recruitment was extremely low during the last 3 years.
5. Management performance:

Status and catch specifications (million lbs.)

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2006/07			15.53	15.75	17.22	N/A	N/A
2007/08	44.8	85.9[A]	20.38	20.51	23.23	N/A	N/A
2008/09	37.6	87.8[B]	20.37	20.32	23.10	24.20	N/A
2009/10	34.3	89.0[C]	16.00	16.00	18.31	22.56	N/A
2010/11[0]		83.1[D]	NA	NA	NA	23.52	N/A
2010/11[7]		73.3[D]	NA	NA	NA	17.88	17.85

Status and catch specifications (1000 t)

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2006/07			7.04	7.14	7.81	N/A	N/A
2007/08	20.32	38.96[A]	9.24	9.30	10.54	N/A	N/A
2008/09	17.06	39.83[B]	9.24	9.22	10.48	10.98	N/A
2009/10	15.56	40.37[C]	7.26	7.26	8.31	10.23	N/A
2010/11[0]		37.69[D]	NA	NA	NA	10.66	N/A
2010/11[7]		33.30[D]	NA	NA	NA	8.11	8.10

The stock was above MSST in 2009/10 and is hence not overfished. Overfishing did not occur during the 2009/10 fishing year. For 2010/2011, "0" is for scenario 0 and "7" is for scenario 7.

Notes:
A – Calculated from the assessment reviewed by the Crab Plan Team in September 2007
B – Calculated from the assessment reviewed by the Crab Plan Team in September 2008 and updated with 2008/09 catch
C – Calculated from the assessment reviewed by the Crab Plan Team in September 2009 and updated with 2009/10 catch
D – Calculated from the assessment reviewed by the Crab Plan Team in September 2010 and from the assessment in May 2011.

6. Basis for the OFL: All table values are in million lbs.

Year	Tier	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	F_{OFL}	Years to define B_{MSY}	Natural Mortality
2008/09	3a	75.1	96.4	1.27	0.33	1995–2008	0.18
2009/10	3a	68.5	99.6	1.39	0.32	1995–2009	0.18
2010/11[0]	3a	62.7	83.1	1.33	0.32	1995-2010	0.18
2010/11[7]	3a	62.6	73.3	1.17	0.32	1995-2010	0.18

Average recruitments during four periods were used to estimate $B_{35\%}$: 1969-1984, 1969-present, 1985-present, and 1995-present. We recommend using the average recruitment during 1995-present, which was used in 2008 and 2009 to set the overfishing limits. There are several reasons for supporting our recommendation. First, estimated recruitment was higher after 1994 than during 1985-1994 and there was a potential regime shift after 1989 (Overland et al. 1999), which corresponded to recruitment in 1995 and later. Second, recruitments estimated before 1985 came from a potentially higher natural mortality than that we used to estimate $B_{35\%}$. Third, high recruitments during the late 1960s and 1970s generally occurred when the spawning stock was primarily located in southern Bristol Bay, while the current spawning stock is mainly in the middle of Bristol Bay. The current flows favor larvae hatched in southern Bristol Bay. Stock productivity (recruitment/mature male biomass) was much higher before the 1976/1977 regime shift: the mean value was 1.857 during brood years 1968-1977 and 0.356 during 1978-2010.

A. Summary of Major Changes

1. Change to management of the fishery: None.

2. Changes to the input data:

a. Catch and bycatch were updated through August 2010 and the 2010 summer trawl survey data were added.

3. Changes to the assessment methodology:

Eleven model scenarios are compared:

Scen.	Var formula for size comp. LL	Initial year proportion estimates	Treatment of re-tow survey data
0	Est[prop]	No	Standard + retow for males & retow for females
1	Obs[prop]	No	Standard + retow for males & retow for females
1a	Obs[prop]	Yes	Standard + retow for males & retow for females
1b	Obs[prop]	No	Standard data only for both males and females
1c	Obs[prop]	No	Standard data for males & retow for females

Sc.	M	Additional mortality (one level for♂, two levels for ♀)	BSFRF survey data, 07 &08	Var formula for size comp. LL	NMFS survey 'Q'	Others	Others
0	0.18	1980-1984 ♂ 76-79&85-93, 80-84♀ (periods selected based Zheng et al. 1995)	Include	Est[prop]	0.896 & Est[Q] for 1970-72		
1	0.18	1980-1984 ♂ 76-79&85-93, 80-84♀	Include	Obs[prop]	0.896 & Est[Q] for 1970-72		
2	0.18	1980-1984 ♂ 76-79&85-93, 80-84♀	Include	Obs[prop]	Above with annually varying multiplying factor (0.8 -1) for 0.896 ♀		
3	0.18	1980-1984 ♂ 76-79&85-93, 80-84♀	Include	Obs[prop]	0.896 & Est[Q] for 1970-72	Three levels of molting prob for ♂	
4	0.18	Predation mortality only on newshell. 1980-1984 high; 76-79&85-93 low	Include	Obs[prop]	0.896 & Est[Q] for 1970-72		
5	0.18	1980-1984 ♂ 76-79&85-93, 80-84 ♀	Include	Obs[prop]	Above with annually varying multiplying factor (0.8 -1) for 0.896 ♀	Three levels of molting prob for ♂	

6	0.18	1980-1984 ♂ 76-79&85-93, 80-84 ♀	Include	Obs[prop]	0.896 & Est[Q] for 1970-72	Three levels of molting prob for ♂	High bycatch rates before 90 from RKC &Tanner fisheries
7	0.18	1980-1984 ♂ 76-79&85-93, 80-84 ♀	Include	Obs[prop]	0.896 & Est[Q] for 1970-72	Three levels of molting prob for ♂	Estimate effective sample size from observed

4. Changes to assessment results:

Male abundance from the 2010 summer trawl survey was lower than expected. Estimated mature male abundance and biomass in 2010 were about 7% lower than those in 2009. Estimated crab abundance and biomass during recent five years were slightly lower than those estimated in 2009.

Summary of numbers of estimated parameters and log likelihood values for 11 scenarios:

Scenario	0	1	1a	1b	1c	2	3	4	5	6	7
Fixed Para.	83	83	47	83	83	83	83	83	83	83	83
Estimated Para.	236	236	272	236	236	279	240	235	283	240	240
Log likelihood	56870	57254	57316	56851	57217	57475	57412	57041	57632	57455	58032

B. Responses to SSC and CPT Comments

1. Responses to the most recent two sets of SSC and CPT comments on assessments in general:

Response to CPT Comments (from May 2010)

"Each stock assessment author should remove the ecosystem section of their chapter and provide it to Liz Chilton for incorporation into the ecosystem consideration chapter."

The ecosystem section of the report has been removed and provided to Liz Chilton.

Response to SSC Comments (from June 2010)

"The SSC requests that the Crab Plan Team and stock assessment authors for red king crab chapters either justify differences between stocks in handling mortality rates for crab pot discards, or adopt a single rate. In order to have greater consistency between assessments, the SSC recommends that catch statistics reported in the executive summary section contain both metric tons and pounds (millions).

It would be useful to consider presenting results from the newly developed projection models for stocks during the next assessment cycle. For example, the SSC notes that the projection model for

Pribilof red king crab could be interpreted as an indication that the stock is approaching an overfished condition. This information should be provided in the SAFE when the assessments are finalized in the fall, even though OFL determinations will be based on Tier 4 considerations."

Recent catches reported in the executive summary section were given in both millions of pounds and metric tons. Pot handling mortality rates for Bristol Bay red king crab and Norton Sound red king crab are assumed to be 0.2. Pot handling mortality rates for red king crab are estimated to be <0.06 from several studies. A higher value (0.2) is used to account for some uncertainties.

2. Responses to the most recent two sets of SSC and CPT comments specific to this assessment:

Response to CPT Comments (from September 2010)

"The CPT ***recommended*** *the following changes to the document: fixing the MSST and MMB values in the summary table; highlighting the most recent year in the plot of F against MMB; and ensuring that the tables and figures in the CIE review transfer correctly to this SAFE chapter."*

These are done.

"The assessment author noted that most of the recent CPT and SSC recommendations will be addressed for the May 2011 CPT meeting. A response to the CIE review will be prepared and submitted to the CPT for the May 2011 meeting. In the fishing mortality/MMB figure, the most recent year should be highlighted. The CPT noted that in the model, the retow and standard survey biomass data were averaged for males and only the retow data were used for female biomass in the model. In May 2011, only the standard survey should be used for males and the retow survey data for females to be consistent with the intent of the retow survey."

The response to the CIE review is included. Due to time constraint, only one scenario (1c) uses the standard tows for males and retows for females. Scenario 1b uses only standard tows for both males and females. All other scenarios use the both standard and retow data for males and retow data for females.

Response to CPT Comments (from May 2010)

"*The CPT noted some inconsistencies in data trends (e.g., BSFRF fit in Fig. 12c of mature male abundance), although the apparent magnitude of these differences may also represent different scaling in the presentation of the results. It was also cautioned that improved model fit attributed to additional mortality factors could be readily attributed to mortality sources other than the bycatch discard that are assumed in some model scenarios. The team noted that detailed results for many of the scenarios (e.g., molting probabilities for scenarios 6 and 7) were not presented in the document. Additional diagnostics, such as bubble plots, would facilitate evaluation of the different scenarios. The lack of detailed results limits the ability of the CPT to evaluate the scenarios.*

CPT looks forward to a revision in May 2011 that addresses previous CPT and SSC comments that were not addressed in this assessment (likelihood profiles, Bayesian approach, effective sample *sizes, and CIE comments). The CPT will review alternative definitions for BMSY time frames. The assessment author should provide alternatives and comment on the appropriateness of each."*

The CIE comments were addressed during the Stock Assessment Workshop in Feb. 2011. Effective sample sizes are examined in Scenario 7. The *likelihood profiles and Bayesian approach* are used to compute OFL and ABC. Alternative definitions for *Bmsy* time frames and detailed results on different scenarios are also presented for scenario 7. Likelihood profiles for q will be examined in the future.

Response to SSC Comments specific to this assessment (from March 2011)

"To address concerns over population-level effects of fishing on recruitment, the SSC recommends that the Crab Plan Team review the basis for the current baseline used to determine productivity of RKC (1995-2010). *In particular, if fishing has contributed to the decline in RKC recruitment after the 1970s, the recent baseline period may not be representative of the productivity of the stock. "*

We support the SSC recommendation on research efforts to understand the effects of the regime shift of 1976/77 and fishing on Bristol Bay red king crab productivity. In the SAFE report, we report the different productivity levels before and after the 1976/77 regime shift, which is the basis for the current baseline. Four different periods are compared for this report. When new results on these effects are available, the baseline can be modified.

Response to SSC Comments specific to this assessment (from Oct. 2010)

"The SSC is still puzzled by one result in the previous SAFE. Namely, Model 5, which set additional mortality for females to 0, had a higher likelihood than Model 3. This should not be possible, because Model 5 had one less parameter. The authors restated that Model 5 had the lowest likelihood but did not explain why this could be the case. The SSC would appreciate receiving an explanation for this result."

We agree with this comment that if it were the case, it would be impossible. However, nowhere in the May 2010 SAFE report does Model 5 have a higher likelihood value than Model 3. In the May 2010 SAFE report, Model 5 has the lowest log likelihood (55180) among all models (ranging from 55180 to 55806) (See the Table in The Summary of Major Changes).

"The SSC agrees with CPT recommendations about items to be addressed by May 2011. First, the authors have not addressed reviewer comments from the June 2009 CIE review. CPT informed the SSC that the author will present a response to the CIE comments during a proposed modeling workshop during February 15-18, 2011. The SSC looks forward to seeing the assessment author's response and plan team recommendations at the April 2011 Council meeting."

The CIE comments were addressed during the Stock Assessment Workshop in Feb. 2011 and the response is included in the report.

"Second, the CPT recommended that the standard survey should be used for the male abundance index and the re-tow survey be used for females, because the standard survey is the baseline and the re-tow survey is intended to address the problem of delayed female molt timing. However, the SSC

would be interested to see an evaluation of model results using the standard survey only versus standard plus re-tow survey results for males for reasons similar to the rationale to include BSFRF survey data in the snow crab assessment. For instance, the selection of the best data to be used in the assessment could involve a sensitivity analysis in which model fit statistics are examined. This could evaluate datasets are most consistent with model projections from one year to the next. In any case, it is important to determine the dataset(s) to be used in the assessment a priori, not post hoc."

Scenario 1b uses only standard survey data and is compared with scenario 1 (both standard and re-survey data) and scenario 1c (standard survey data for males and re-survey data for females, CPT option). The likelihood value is much higher for Scenario 1 than scenarios 1b and 1c.

"Third, further sensitivity analysis should be done with respect to data weighting, catchability parameters, and mortality parameters. Also, rationale for model choices should be enhanced. Finally, the extent of expansion of the population northward should be examined. In that light, consideration should be given as to whether a tagging study in the north would be useful to estimate movement probability."

Data weighting was examined during the past SAFE reports. Due to time constraint, the only data weighting examined in this report is effective sample sizes. Different scenarios are used to examined catchability parameters and mortality parameters. We do not have time to examine the expansion of the population northward. A tagging study in the north would understand crab migration. Few mature crab occur in the north outside of the current stock definition. We need to understand whether the northern crab participate in the stock reproductivity before including them in the model. This issue is similar to snow crab, which are found all way to Norton Sound.

Response to SSC Comments specific to this assessment (from June 2010)

"The SSC agrees that Model 3 is suitable for basing stock status determination after the summer survey data are incorporated later this year. This model estimates additional natural mortality for males and females, uses the BSFRF survey, and does not estimate molting parameters. However, the SSC notes that Model 5, which sets additional mortality for females to 0, has a higher likelihood. This should not be possible, because Model 5 has one less parameter. This needs to be rechecked. It may be that these sex-specific differences in additional natural mortality are not needed. Also, the SSC recommends that the authors consider using AIC for model comparison for the sake of parsimony. (This can only be done when the same data are used."

Model 5 has the lowest log likelihood (55180) among all models (ranging from 55180 to 55806) (See the Table in The Summary of Major Changes). AIC may be used for model comparison in the future.

"The SSC concurs with the CPT that the stock is in Tier 3. The SSC also agrees with the selected range of years, 1995 to the current year, for average recruitment and $B_{35\%}$. The SSC agrees with the authors' plan to continue to refine the model in terms of likelihood profiles for M and q, sensitivity to data weighting, use of Bayesian methods, and other topics described on pages 137 – 142 of the May 2010 SAFE."

Eleven model scenarios are presented in this report to address comments. Likelihood profiles for M and sensitivity to data weighting were examined in the past SAFE reports.

"The SSC notes that the time periods used for estimating survey selectivity do not match the time periods used for estimating survey catchability q. This does not seem realistic, since shifts in gear would be expected to influence both selectivity and q. The SSC requests that the authors examine a model with common time periods for q and selectivity. "

The survey catchability is not estimated except during 1970-1972. The catchability from the double-bag experiment was used for all periods except 1970-1972. The authors tried to estimate three sets of survey catchability and selectivity; however, parameter confounding seems to be a problem with estimating too many sets of survey catchability. There seems to be a gear problem with the surveys in 1970-1972, so a separate set of catchability and selectivity was estimated.

"On page 165, the author states that one explanation of the extra female mortality during 1976 through 1979 and 1985 through 1993 was increased bycatch (among other things). If the primary cause of the additional mortality is thought to be bycatch mortality, then this should be modeled as female fishing mortality, rather than natural mortality, because the fishery impact would be over a discrete season, rather than an entire year. At a minimum, it should clarify and justify how the additional mortality was modeled."

Extra mortality is examined through different scenarios.

"On the bottom of page 166, the SSC notes that the pot male fishing mortality rate in the SAFE is not correct. This value should be 0.2. "

The handling mortality rate is 0.2. However, the pot female fishing mortality rate is about 2% of those for males.

"The SSC notes that the values for 2009/10 OFL in the SAFE chapter and the ACL document do not match. The author should explain the reason for the difference."

We think that we finally got them almost the same. The difference is from the earlier version of the ACL analysis, which has some different initial conditions and weightings.

"For the Ecosystem Considerations chapter, the importance of king crab consumption of fish discards should be examined. This has been observed in the Barents Sea, where king crab distribution overlaps intensive fishing activity (G. Hunt, pers. comm.). Thus, it would be interesting to examine trajectories of crab populations in relation to the amount of groundfish discards."

This is an interesting observation. We will explore this issue in the future.

"If time permits, it would be useful for the CPT and SSC to see the CIE review report at their September/October 2010 meetings."

The CIE review comments were addressed during the Stock Assessment Workshop in Feb. 2011. We attached our responses to this report.

3. Responses to the recommendations from the Stock Assessment Workshop in Feb. 2011:

"1) Justify why the choice of switching the variance terms in the robust multinomial likelihood to the observed proportions-at-length for all scenarios, rather than switching back to the base scenario that used the predicted proportions-at-length. Bubble plots of the residual patterns using either formulation should be shown sideby-side for comparative purposes. There is some concern that very small sample sizes may create large residuals."

Switching the variance terms are suggestions from the CIE review and the CPT. The likelihood value is much higher with the variances from the observed proportions than estimated proportions. The plots of residual patterns are following each other, although they are not side-by-side.

"2) Provide a table of model parameters and describe which parameters are fixed and which are estimated (as per terms of reference) as well as the corresponding parameter bounds assumed. If fixed then please justify the fixed value."

The fixed parameters are listed in Table 5(0) for scenario 0. Most other scenarios have the same fixed parameters. These fixed parameters are explained in the Appendix (section of Parameters Estimated Independently). Estimated parameters are listed in Table 6 for scenario 0.

3) A suggestion to run a sensitivity analysis with and without retow data. The retow data should be treated consistently in both the survey abundance estimate and the population assessment model."

Scenario 1b is the scenario with only standard survey data, which can be compared with scenario 1 with both standard and re-tow data for males and re-tow data for females and scenario 1c with only standard data for males and re-tow data for females.

"4) The model is initialized with the 1968 size distribution data; the model should be run with estimated initial conditions and evaluate the effects on management quantities."

Scenario 1a estimates initial length/sex proportions, which has similar abundance estimates with scenario 1. Scenario 1a has additional 36 parameters and its log likelihood also increases, but the increase is much less relative to other scenarios with high numbers of parameters.

4. Responses to the recommendations from the Stock Assessment Workshop in Feb. 2011:

WEAKNESSES

Dr. Billy Ernst

• *Some relevant fisheries data were omitted from the stock assessment. The time series of catch-per-unit effort (catch-per-pot) was not used in the stock assessment, and it would have been useful to have a second index of relative abundance.*

Reply: If survey data were not available, catch-per-potlift data would have to be used as a relative abundance index. Because soak times are not available for most years and changes occurred in pot limits and escapement rings over time, it is difficult to standardize the catch-per-potlift data.

• *There is a potential bias with inter-annual variability in the EBS NMFS trawl survey abundance estimates due to timing of the survey, spatial dynamics and environmental variability.*

Reply: Good point. Scenario 2 addresses some of these problems.

• Parameter uncertainty in fixed model quantities was not appropriately addressed in the stock assessment document.

Reply: When relatively good information is available, we tend to fix the parameter values to reduce parameter confounding. Sensitivity analysis can be used to examine the uncertainty.

• There is a lack of a general conceptual model that integrates life history and spatial dynamics. This would help to interpret the survey data, model configuration and relevant statistics for management.

Reply: The general conceptual model for recruitment has been developed (Tyler and Kruse, 1996). It is difficult to formulate a spatial model at this point in time because appropriate data are not available to estimate parameters.

• There is a lack of theoretical support for variable natural mortality scenarios. These might be replaced by more mechanistic bycatch mortality scenarios.

Reply: This is a good point, and scenarios 4 and 6 are used to examine high predation and high bycatch mortality rates. SAFE reports in 2009 and 2010 examined scenarios with extreme high bycatch.

• The stock assessment document is extensive but incomplete in describing all model equations and formulations.

Reply: The SAFE report has been revised in 2010 to document all equations and formulations in response to this concern (Appendix A and text in the main stock assessment document for spring 2011).

• The selection of recruitment time series interval for reference points calculations is debatable.

Reply: Good point, agree, and it is a hot topic for the CPT too.

Dr. Nick Caputi:

• The use of different natural mortality rates for different periods appears to be justified to explain the declines in abundance in the early 1980s which may be linked to regime shifts, predation, bycatch or effects of trawling. The changes in the mortality rates for males and females for different time periods provides a better fit to the data but it is not clear what the biological processes may be to justify this assumption.

Reply: The SAFE reports in 2009 and 2010 discussed potential biological explanations: predation, older ages, and diseases; however, we acknowledge that specific explanations are difficult to verify,

• The model has been developed for the whole stock which hides some interesting spatial dynamics that is occurring in the fishery such as (a) differential rates of migration between inshore and offshore; and (b) changes in the spatial distribution of the spawning stock that may have affected the recruitment abundance and distribution.

Reply: Agree. A spatial model may be an improvement from the current model. However, due to lack of data, it is difficult to develop a detailed spatial model at this point in time.

• The complex state/federal decision rule framework is a weakness in the stock assessment process. The step function being used in the Alaskan state decision framework for setting quotas (Fig.1 of Zheng and Siddeek 2009) may make it difficult if the biological estimates are close to the threshold

levels given there is some uncertainty associated with these estimates. A slope function between the harvest rate and biomass may provide a better representation for the decision rule.

Reply: This is a good recommendation for consideration by the Alaska Board of Fisheries. There are pros and cons for the state harvest strategy in term of assessment errors. Under the state harvest strategy, the impact of errors would be bigger if the estimated abundance is close to the threshold levels and would be less if the estimated abundance is away from the threshold levels.

• *The stock assessment process does not utilize the fishing effort and catch rate (CPUE) information for the pot fishery. This may be a valuable data set that may enhance the stock assessment process. Further comments on this analysis are provided below.*

Reply: if survey data were not available, catch-per-potlift data would have to be used as a relative abundance index. Because soak times are not available for most years and changes occurred in pot limits and escapement rings over time, it is difficult to standardize the catch-per-potlift data.

• *Potential underestimates of the Tanner and RKC fisheries bycatch of RKCs that may affect the estimate of natural mortality. Consideration should be given to the effect that: (a) rate of retention for undersize in traps may be greater during periods of high catch rate as escape gaps may not function as well; and (b) higher bycatch mortality rate may be associated with handling in periods of high catch rate.*

Reply: Agree. Scenario 6 was added to address this problem.

• *One of the hotspots of abundance of RKCs from the annual trawl survey regularly occurs on the boundary of the trawl area near the coast. This could result in a significant underestimate of the biomass if there is a high abundance in the non-surveyed areas along the coast.*

Reply: Agree. This case could occur for mature female and juvenile crabs. Scenario 2 was added to address the female catchability issue. Survey selectivity deals with the juvenile crabs.

• *A useful addition to the stock assessment document would be a description of the life cycle that provides an understanding of the key biological processes taking place over time and space. This should include time and place of primiparous and multiparous mating, hatching, larval period and movement, settlement period and location, growth, time and size at maturity, time to legal size, molt frequency and timing, migration patterns of males and females. Some of this information is directly relevant to the stock assessment and other information may be supplementary to the stock assessment process. Development of a spatial-temporal conceptual model of the life history of RKC and the fisheries affecting it would be useful.*

Reply: Agree. Life history has been added to the SAFE report for 2010. A more complete spatial-temporal conceptual model can be added in the future.

ToRs 2 and 3: Recommendations of alternative model assumptions and estimators

Dr. Billy Ernst:

(a) *Re-analyze EBS NMFS trawl survey data using an alternative likelihood based geostatistical approach (Roa and Niklitschek 2007). If the same approach is used, the criteria for estimating abundance and its variance across the entire time series should be unified.*

Reply: Agree. NMFS scientists conduct area-swept estimates of the trawl survey data. We encourage NMFS scientists to examine this approach for Bristol Bay red king crab data as well as other crab stock data.

(b) Include new mechanistic scenarios that address more clearly the decline in female and male abundance during the early 1980s (use Griffin et al. 1983 bycatch rates to complete the time series).

Reply: Different scenarios were made to investigate this issue. The most difficult task is to deal with the crab abundances in the 65-120 mm size range that were highly abundant with low bycatch selectivity, but disappeared quickly during the early 1980s. The estimated bycatches based on Griffin et al. (1983) study were low relative to the area-swept abundance (Figure 1r) and the selectivity was similar to the current model estimates. These bycatch rates could not explain the abundance decline. Some NMFS scientists suggested using the ratio of bycatch to the number of legal males in 1982 and assumed all other years have the same ratio to estimate bycatches. This approach requires a steady population state assumption during the 1970s and early 1980s. Under this assumption and ignoring the stock length structures, estimated bycatches could explain the abundance decline by a certain degree for male crabs but failed to explain the female abundance decline. Unfortunately, the stock changed dramatically during late 1970s and early 1980s and was far from a steady state (Figures 2r and 3r). The length structure in 1982 was extremely different from the other years (Figure 2r).

We investigated a scenario of high predation mortality for newshell crabs (scenario 4) and high bycatch rates (scenario 6) in the current updated SAFE report.

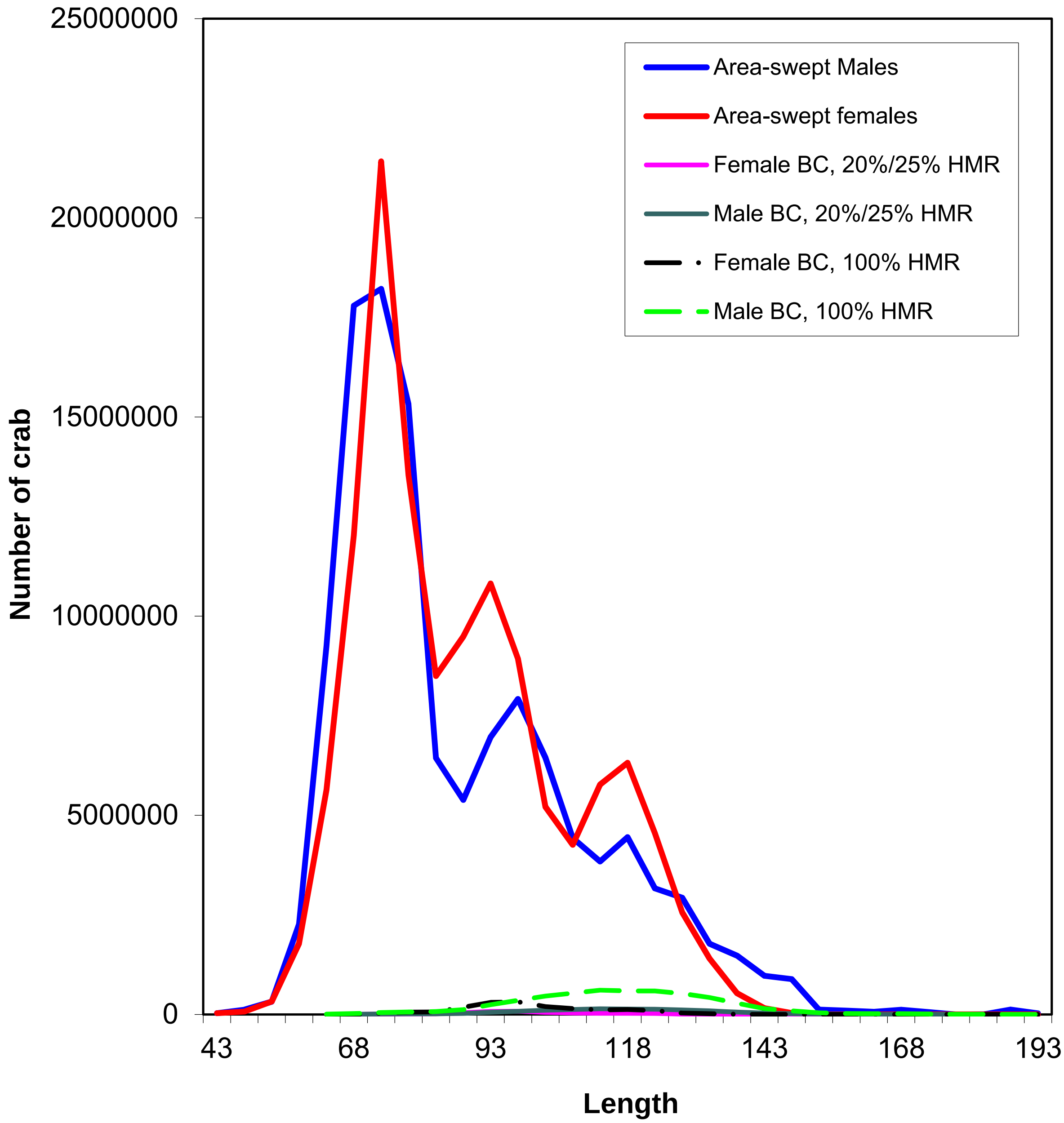

Figure 1r. Comparison of area-swept estimates of abundance and estimates of bycatch mortality (Griffin et al., 1983) in 1982. Two bycatch mortality rates are used: 20% for the red king fishery and 25% for the Tanner crab fishery and 100% for both red king and Tanner crab fisheries. Estimated bycatches were a very small proportion of the survey abundance.

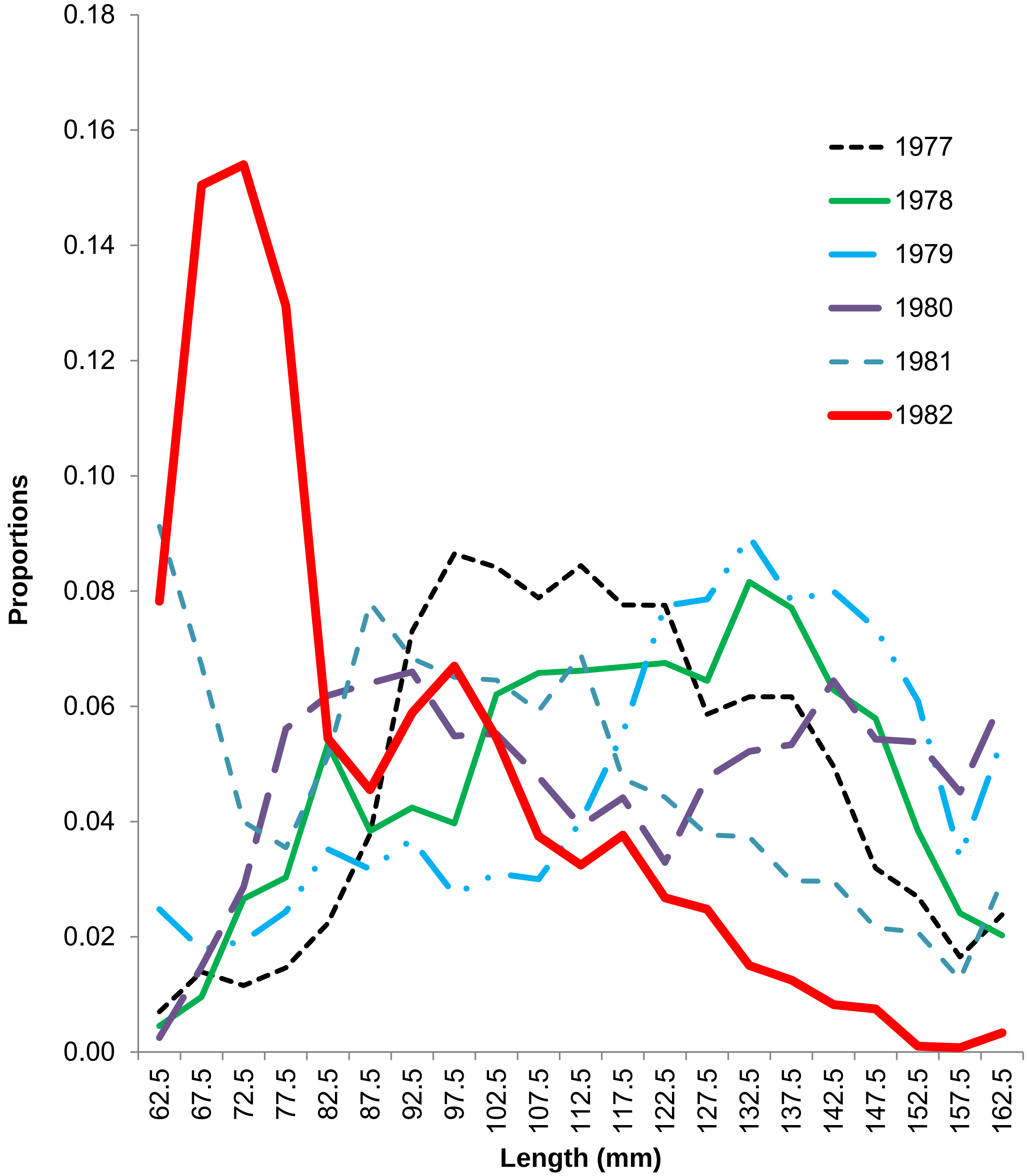

Figure 2ra. Length compositions of area-swept estimates of male crabs during 1977-1982. Length structure in 1982 was completely different from the other years. It is invalid to assume that the length structures are about the same during these years.

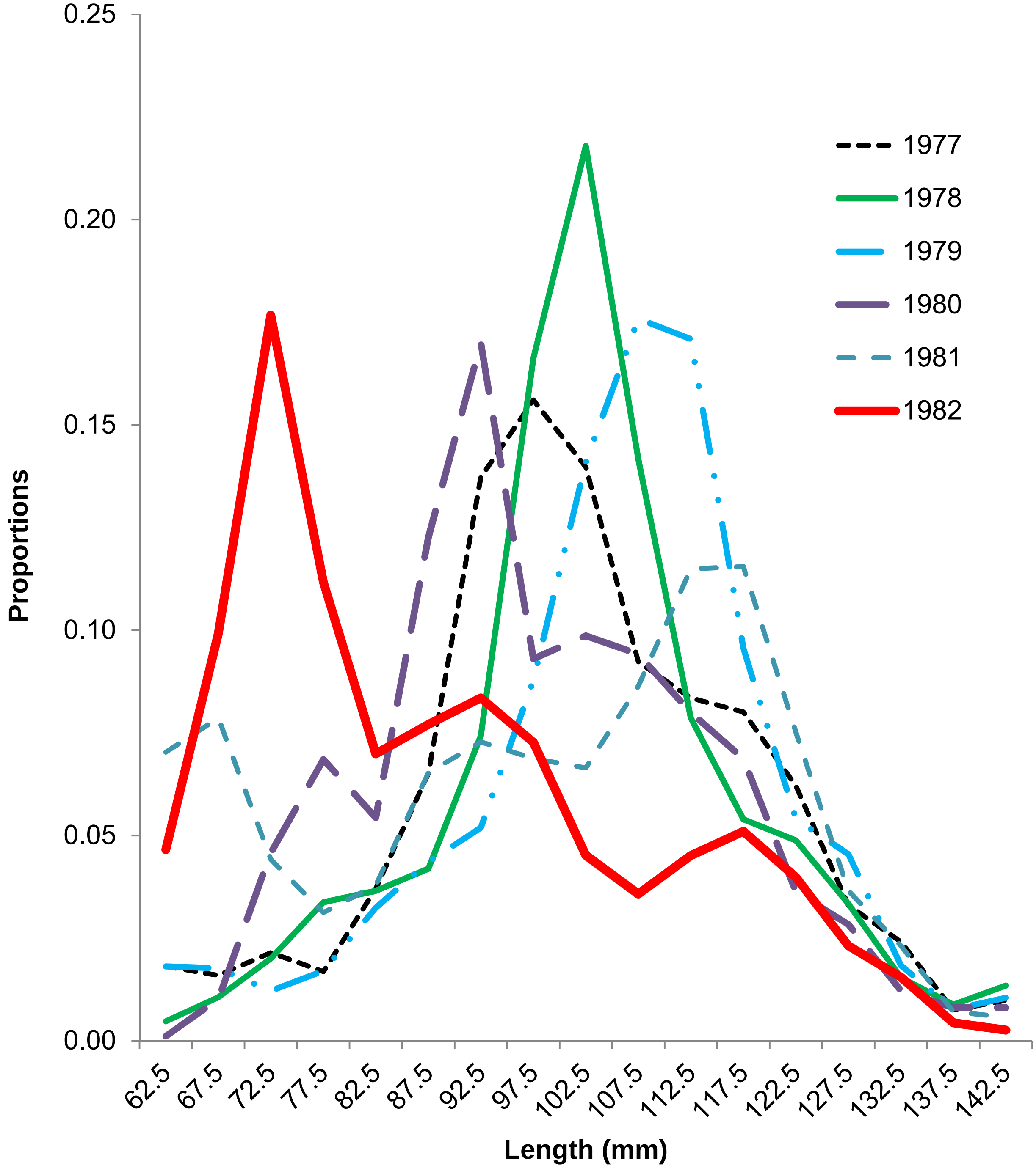

Figure 2rb. Length compositions of area-swept estimates of female crabs during 1977-1982. Length structure in 1982 was completely different from the other years. It is invalid to assume that the length structures are about the same during these years.

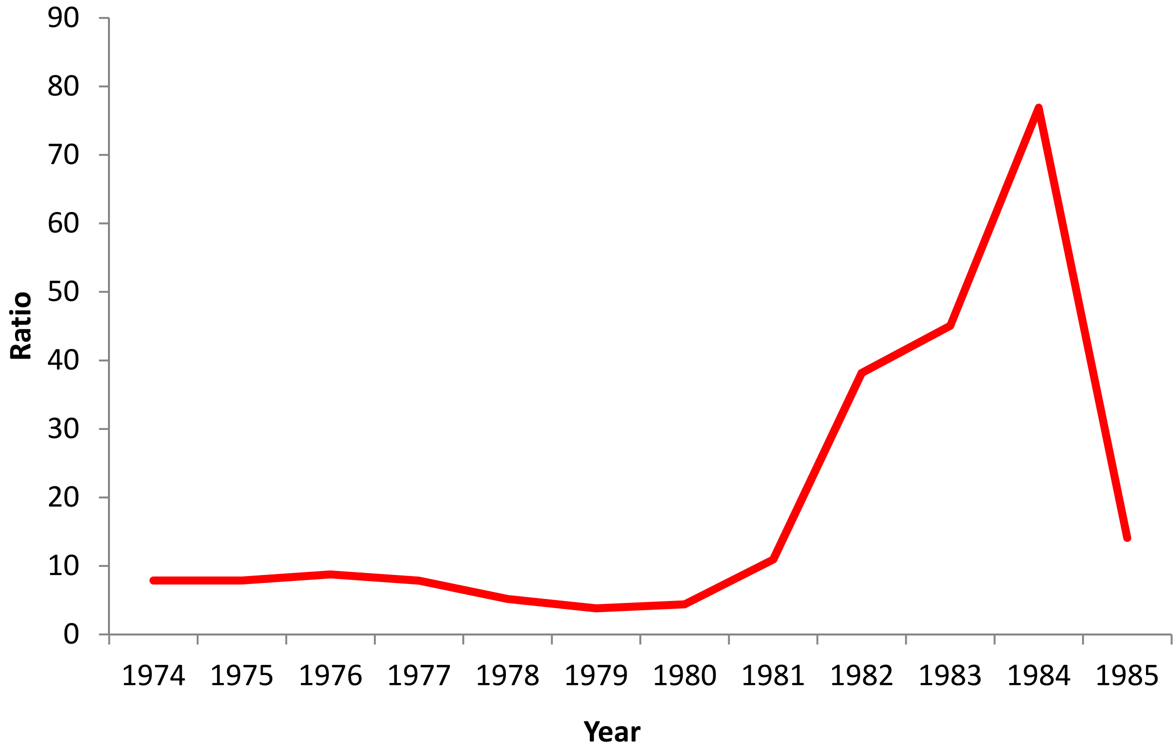

Figure 3r. Ratios of survey abundance of 80-134 mm males and 70+ mm females divided by survey legal male abundance. Although some bycatches are smaller than 70 mm for females and smaller than 80 mm for males, 80-134 mm males and 70+ mm females basically represent the bycatch population. The ratio in 1982 was much higher than those before 1982. It is invalid to assume that the length structures are about the same during these years.

(c) Explore alternative configurations for initial conditions and evaluate their effects on the assessment parameters.

Reply: Initial conditions for different parameters were varied when the model was developed to check the robustness of the likelihood optimization.

(d) Improve diagnostics and comparative analyses of different model configuration results (scenarios), including fixed parameter values, effect of likelihood weights, initial conditions.

Reply: A good suggestion. Effects of likelihood weights were examined and reported in the 2009 SAFE report. Eight scenarios are compared in the current updated SAFE report.

(e) More precisely assess the effect of including and excluding the BSFRF survey, with an emphasis on current biomass estimates (males and females) and likelihood value of different pieces of information.

Reply: This was done in the 2010 SAFE Fall report.

(f) *Use observed proportions as opposed to predicted ones in the variance term of the normal likelihood function.*

Reply: Good suggestion. We implemented it in scenario 1.

(g) *Compute implicit sample sizes and variances for each piece of information and compare it to the ones used in the assessment.*

Reply: Effective sample sizes have been estimated and compared with the assumed values. In scenario 7, we examined a new approach to estimate effective sample sizes.

(h) *Consider a formal statistical approach to estimate the male size transition matrix externally, using historical tagging data (Punt et al., 2009).*

Reply: The current approach is a statistical approach. Different assumptions are needed for using the approaches by Punt et al (2009). We may examine different approaches in the future.

(i) *If male molting probabilities are estimated outside of the model (from tagging data), then there should be no need to use old shell and new shell categories in the dynamics of the model. This would simplify model assumptions and the number of parameters to be estimated.*

Reply: Good point, one that we have thought about before. The problem is that the tagging data are primarily from 1960s and early 1970s, and during these periods, oldshell crab abundances were low and estimated molting probabilities were much higher than those during 1980s-2000s. We examined a scenario with three levels of molting probabilities over time (scenario 3).

(j) *Assess mature male molting time. If a fraction of mature males are not capable of mating during the survey time (Dew 2009), then the current calculation of mature males available for mating (>120 mm) would be overestimated.*

Reply: Dew (2009) assumed that oldshell mature males stay inshore for mating. The re-tow data during the last 12 years did not support this assumption.

(k) *Because an unknown fraction of the population remains unsampled in the survey and this proportion varies from year to year, it would be appropriate to implement a scenario that allows for inter-annual variation in survey availability. Ideally this variation could be modeled based on oceanographic data during the survey, or available year around from ROMs outputs.*

Reply: Good point. However, this mainly applies to females. This can be tried by allowing some variation of annual survey selectivities. The difficulty is knowing how much variation should be allowed. We examined a scenario of varying survey catchabilily of females over time (scenario 2).

(l) *Implement a management strategy evaluation to assess harvest rates under different productivity scenarios.*

Reply: This is a good idea. This will be a task to consider in the near future.

Dr. Nick Caputi:
Recommendations for alternative model configurations and assumptions are:

(a) *The move to crab rationalization has resulted in improved economic data collection that can be used to set harvest rate targets for improved profitability of the fishery.*

Reply: This requires economists' expertise. We will explore this with our economists.

(b) *Average recruitment during 1968-2008, 1985-2008, 1995-2008 were considered in setting overfishing limits - the choice of B35% should take into account the stock-recruitment relationship so that the level of mature biomass is sufficiently high that if good environmental conditions occur then good recruitments will occur.*

Reply: The S-R relationships were used for determining the current state harvest strategy (target harvest).

(c) *The assessment of the mature male biomass (MMB) contributing to the mating each year should take into account the decline in molting probability with size which means that the larger males may be contributing proportionally more to mating than smaller males that are molting most years.*

Reply: Because large males are heavier than small males, the mature male biomass estimate more or less takes this into account. The state harvest strategy (target harvest) provides further weighting for large males. How many mature females a mature male can mate during a mating season will affect the effective spawning biomass. The number of mature females a mature male can mate increases with the size of mature male (see Zheng et al. 1995). This is currently an area of debate.

(d) *Alternative hypotheses for cause of mortality in the early 1980s should be explored e.g. an additional mortality at different time periods, bycatch in the RKC and/or Tanner crab fisheries. Information on size structure should be taken into account to obtain improved estimates of bycatch when observer data was not available as well the effectiveness of the escape gaps and bycatch mortality rates at different levels of catch rate.*

Reply: We have investigated some scenarios on this line. In the current updated SAFE report, we examined two scenarios, scenario 4 for high predation mortality and scenario 6 for high bycatch rates.

(e*)* *Sensitivity analysis of trawl survey catchability estimates.*

Reply: We examined variation of trawl survey catchability over time for females (scenario 2). This issue will be examined further when new data become available.

C. Introduction

1. Species

Red king crab (RKC), *Paralithodes camtschaticus* in Bristol Bay, Alaska.

2. General distribution

Red king crab inhabit intertidal waters to depths >200 m of the North Pacific Ocean from British Columbia, Canada, to the Bering Sea, and south to Hokkaido, Japan. RKC are found in several areas of the Aleutian Islands and eastern Bering Sea.

3. Stock Structure

The State of Alaska divides the Aleutian Islands and eastern Bering Sea into three management registration areas to manage RKC fisheries: Aleutian Islands, Bristol Bay, and Bering Sea (Alaska Department of Fish and Game (ADF&G) 2005). The Aleutian Islands area covers two stocks, Adak and Dutch Harbor, and the Bering Sea area contains two other stocks, the Pribilof Islands and Norton Sound. The largest stock is found in the Bristol Bay area, which includes all waters north of the latitude of Cape Sarichef ($54^{o}36'$ N lat.), east of $168^{o}00'$ W long., and south of the latitude of Cape Newenham ($58^{o}39'$ N lat.) (ADF&G 2005). Besides these five stocks, RKC stocks elsewhere in the Aleutian Islands and eastern Bering Sea are currently too small to support a commercial fishery. This report summarizes the stock assessment results for the Bristol Bay RKC stock.

4. Life History

Life history of RKC is complex. Fecundity is a function of female size, ranging from several tens of thousands to a few hundreds of thousands (Haynes 1968). The eggs are extruded by females and fertilized in the spring and are held by females for about 11 months (Powell and Nickerson 1965). Fertilized eggs are hatched in spring, most during the April to June period (Weber 1967). Primiparous females are bred a few weeks earlier in the season than multiparous females.

Larval duration and juvenile crab growth depend on temperature (Stevens 1990; Stevens and Swiney 2007). The RKC mature at 5–12 years old, depending on stock and temperature (Stevens 1990) and may live >20 years (Matsuura and Takeshita 1990), with males and females attaining a maximum size of 227 and 195 mm carapace length (CL), respectively (Powell and Nickerson 1965). For management purposes, females >89 mm CL and males > 119 mm CL are assumed to be mature for Bristol Bay RKC. Juvenile RKC molt multiple times per year until age 3 or 4; thereafter, molting continues annually in females for life and in males until maturity. After maturing, male molting frequency declines.

5. Fishery

The RKC stock in Bristol Bay, Alaska, supports one of the most valuable fisheries in the United States (Bowers et al. 2008). The Japanese fleet started the fishery in the early 1930s, stopped fishing from 1940 to 1952, and resumed the fishery from 1953 until 1974 (Bowers et al. 2008). The Russian fleet fished for RKC from 1959 through 1971. The Japanese fleet employed primarily tanglenets with a very small proportion of catch from trawls and pots. The Russian fleet used only tanglenets. United States trawlers started to fish for Bristol Bay RKC in 1947, and effort and catch declined in the 1950s (Bowers et al. 2008). The domestic RKC fishery began to expand in the late 1960s and peaked in 1980 with a catch of 129.95 million lbs (58,943 t), worth an estimated $115.3 million ex-vessel value (Bowers et al. 2008). The catch declined dramatically in the early 1980s and has stayed at low levels during the last two decades (Table 1). After the stock collapse in the early 1980s, the Bristol Bay RKC fishery took place during a short period in the fall (usually lasting about a week), with the catch quota based on the stock assessment conducted in the previous summer (Zheng and Kruse 2002). As a result of new regulations for crab rationalization, the fishery was open longer from October 15 to January 15, beginning with the 2005/2006 season. With the implementation of crab rationalization, historical guideline harvest levels (GHL) were changed to a total allowable catch (TAC). The GHL/TAC and actual catch are compared in Table 2. The implementation errors are quite high for some years, and total actual catch from 1980 to 2007 is about 6% less than the sum of GHL/TAC over that period (Table 2).

6. Fisheries Management

King and Tanner crab stocks in the Bering Sea and Aleutian Islands are managed by the State of Alaska through a federal king and Tanner crab fishery management plan (FMP). Under the FMP, management measures are divided into three categories: (1) fixed in the FMP, (2) frame worked in the FMP, and (3) discretion of the State of Alaska. The State of Alaska is responsible for developing harvest strategies to determine GHL/TAC under the framework in the FMP.

Harvest strategies for the Bristol Bay RKC fishery have changed over time. Two major management objectives for the fishery are to maintain a healthy stock that ensures reproductive viability and to provide for sustained levels of harvest over the long term (ADF&G 2005). In attempting to meet these objectives, the GHL/TAC is coupled with size-sex-season restrictions. Only males≥6.5-in carapace width (equivalent to 135-mm carapace length, CL) may be harvested and no fishing is allowed during molting and mating periods (ADF&G 2005). Specification of TAC is based on a harvest rate strategy. Before 1990, harvest rates on legal males were based on population size, abundance of prerecruits to the fishery, and postrecruit abundance, and rates varied from less than 20% to 60% (Schmidt and Pengilly 1990). In 1990, the harvest strategy was modified, and a 20% mature male harvest rate was applied to the abundance of mature-sized (≥120-mm CL) males with a maximum 60% harvest rate cap of legal (≥135-mm CL) males (Pengilly and Schmidt 1995). In addition, a minimum threshold of 8.4 million mature-sized females (≥90-mm CL) was added to existing management measures to avoid recruitment overfishing (Pengilly and Schmidt 1995). Based on a new assessment model and research findings (Zheng et al. 1995a, 1995b, 1997a, 1997b), the Alaska Board of Fisheries adopted a new harvest strategy in 1996. That strategy had two mature male harvest rates: 10% when effective spawning biomass (ESB) is between 14.5 and 55.0 million lbs and 15% when ESB is at or above 55.0 million lbs (Zheng el al. 1996). The maximum harvest rate cap of legal males was changed from 60% to 50%. An additional threshold of 14.5 million lbs of ESB was also added. In 1997, a minimum threshold of 4.0 million lbs was established as the minimum GHL for opening the fishery and maintaining fishery manageability when the stock abundance is low. In 2003, the Board modified the current harvest strategy by adding a mature harvest rate of 12.5% when the ESB is between 34.75 and 55.0 million lbs. The current harvest strategy is illustrated in Figure 1.

D. Data

1. Summary of New Information

New data include commercial catch and bycatch in 2009/2010 and the 2010 summer trawl survey.

2. Catch Data

Data on landings of Bristol Bay RKC by length and year and catch per unit effort were obtained from annual reports of the International North Pacific Fisheries Commission from 1960 to 1973 (Hoopes et al. 1972; Jackson 1974; Phinney 1975) and from the ADF&G from 1974 to 2008 (Bowers et al. 2008). Bycatch data are available starting from 1990 and were obtained from the ADF&G observer database and reports (Bowers et al. 2008; Burt and Barnard 2006). Sample sizes for catch by length and shell condition are summarized in Table 3. Relatively large samples were taken from the retained catch each year. Sample sizes for trawl bycatch were the annual sums of length frequency samples in the National Marine Fisheries Service (NMFS) database.

(i). Catch Biomass

Retained catch and estimated bycatch biomasses are summarized in Table 1. Retained catch and estimated bycatch from the directed fishery include both the general open access fishery (i.e., harvest not allocated to Community Development Quota [CDQ] groups) and the CDQ fishery. Starting in 1973, the fishery generally occurred during the late summer and fall. Before 1973, a small portion of retained catch in some years was caught from April to June. Because most crab bycatch from the groundfish trawl fisheries occurred during the spring, the years in Table 1 are one year less than those from the NMFS trawl bycatch database to approximate the annual bycatch for reporting years defined as June 1 to May 31; e.g., year 2002 in Table 1 corresponds to what is reported for year 2003 in the NMFS database. Catch biomass is shown in Figure 2.

(ii). Catch Size Composition

Retained catch by length and shell condition and bycatch by length, shell condition, and sex were obtained for stock assessments. From 1960 to 1966, only retained catch length compositions from the Japanese fishery were available. Retained catches from the Russian and U.S. fisheries were assumed to have the same length compositions as the Japanese fishery during this period. From 1967 to 1969, the length compositions from the Russian fishery were assumed to be the same as those from the Japanese and U.S. fisheries. After 1969, foreign catch declined sharply and only length compositions from the U.S. fishery were used to distribute catch by length.

(iii). Catch per Unit Effort

Catch per unit effort (CPUE) is defined as the number of retained crabs per tan (a unit fishing effort for tanglenets) for the Japanese and Russian fisheries and the number of retained crabs per potlift for the U.S. fishery (Table 4). Soak time, while an important factor influencing CPUE, is difficult to standardize. Furthermore, complete historical soak time data from the U.S. fishery are not available. Based on the approach of Balsiger (1974), all fishing effort from Japan, Russia, and U.S. were standardized to the Japanese tanglenet from 1960 to 1971, and the CPUE was standardized as crabs per tan. The U.S. CPUE data have similar trends as survey legal abundance after 1971 (Figure 3). Due to the difficulty in estimating commercial fishing catchability and the ready availability of NMFS annual trawl survey data, commercial CPUE data were not used in the model.

3. NMFS Survey Data

The NMFS has performed annual trawl surveys of the eastern Bering Sea since 1968. Two vessels, each towing an eastern otter trawl with an 83 ft headrope and a 112 ft footrope, conduct this multispecies, crab-groundfish survey during the summer. Stations are sampled in the center of a systematic 20 X 20 nm grid overlaid in an area of ≈140,000 nm^2. Since 1972 the trawl survey has covered the full stock distribution except in nearshore waters. The survey in Bristol Bay occurs primarily during late May and June. Tow-by-tow trawl survey data for Bristol Bay RKC during 1975-2010 were provided by NMFS.

Abundance estimates by sex, carapace length, and shell condition were derived from survey data using an area-swept approach without post-stratification (Figures 4 and 5). If multiple tows were made for a single station in a given year, the average of the abundances from all tows was used as the estimate of abundance for that station. Until the late 1980s, NMFS used a post-stratification approach, but subsequently treated Bristol Bay as a single stratum. If more than one tow was conducted in a station because of high RKC abundance (i.e., the station is a "hot spot"), NMFS regards the station as a separate stratum. Due to poor documentation, it is difficult to duplicate past NMFS post-stratifications. A "hot spot" was not surveyed with multiple tows during the early years. Two such "hot spots" affected the survey abundance estimates greatly: station H13 in 1984 (mostly juvenile crabs 75-90 mm CL) and station F06 in 1991 (mostly newshell legal males). The tow at station F06 was discarded in the older NMFS abundance estimates (Stevens et al. 1991). In this study, all tow data were used. NMFS re-estimated historic areas-swept in 2008 and re-estimated area-swept abundance as well, using all tow data. We used area-swept abundances estimated by NMFS in July 2010 in this report.

In addition to standard surveys, NMFS also conducted some surveys after the standard surveys to assess mature female abundance. Two surveys were conducted for Bristol Bay RKC in 1999, 2000, 2006-2010: the standard survey that was performed in late May and early June (about two weeks earlier than historic surveys) in 1999 and 2000 and the standard survey that was performed in early June in 2006-2010 and resurveys of 31 stations (1999), 23 stations (2000), 31 stations (2006, 1 bad tow and 30 valid tows), 32 stations (2007-2009) and 23 tows (2010) with high female density that was performed in late July, about six weeks after the standard survey. The resurveys were necessary because a high proportion of mature females had not yet molted or mated prior to the standard surveys (Figure 6). Differences in area-swept estimates of abundance between the standard surveys and resurveys of these same stations are attributed to survey measurement errors or to seasonal changes in distribution between survey and resurvey. More large females were observed in the resurveys than during the standard surveys in 1999 and 2000 because most mature females had not molted prior to the standard surveys. As in 2006, area-swept estimates of males >89 mm CL, mature males, and legal males within the 32 resurvey stations in 2007 were not significantly different between the standard survey and resurvey (P=0.74, 0.74 and 0.95) based on paired t-tests of sample means. However, similar to 2006, area-swept estimates of mature females within the 32 resurvey stations in 2007 are significantly different between the standard survey and resurvey (P=0.03) based on the t-test. To maximize use of the survey data, we used data from both surveys to assess male abundance but only the resurvey data, plus the standard survey data outside the resurveyed stations, to assess female abundance during these six years.

For 1968-1970 and 1972-1974, abundance estimates were obtained from NMFS directly because the original survey data by tow were not available. There were spring and fall surveys in 1968 and 1969. The average of estimated abundances from spring and fall surveys was used for those two years. Different catchabilities were assumed for survey data before 1973 because of an apparent change in survey catchability. A footrope chain was added to the trawl gear starting in 1973, and the crab abundances in all length classes during 1973-1979 were much greater than those estimated prior to 1973 (Reeves et al. 1977).

4. Bering Sea Fisheries Research Foundation Survey Data

The BSFRF conducted trawl surveys for Bristol Bay red king crab in 2007 and 2008 with a small-mesh trawl net and 5-minute tows. The surveys occurred at similar times with the NMFS standard surveys and covered about 97% of the Bristol Bay area. Few Bristol Bay red king crab were outside of the BSFRF survey area. Because of small mesh size, the BSFRF surveys weree expected to catch nearly all red king crabs within the swept area. Crab abundances of different size groups were estimated by the Kriging method. Mature male abundances were estimated to be 22.331 and 19.747 million in 2007 and 2008 with a CV of 0.0634 and 0.0765.

E. Analytic Approach

1. History of Modeling Approaches

To reduce annual measurement errors associated with abundance estimates derived from the area-swept method, the ADF&G developed a length-based analysis (LBA) in 1994 that incorporates multiple years of data and multiple data sources in the estimation procedure (Zheng et al. 1995a). Annual abundance estimates of the Bristol Bay RKC stock from the LBA have been used to manage the directed crab fishery and to set crab bycatch limits in the groundfish fisheries since 1995 (Figure 1). An alternative LBA (research model) was developed in 2004 to include small size groups for federal overfishing limits. The crab abundance declined sharply during the early 1980s. The LBA estimated natural mortality for different periods of years, whereas the research model estimated additional mortality beyond a basic constant natural mortality during 1976-1993. In this report, we present only the research model that was fit to the data from 1968 to 2010.

2. Model Description

a. The original LBA model was described in detail by Zheng et al. (1995a, 1995b) and Zheng and Kruse (2002). The model combines multiple sources of survey, catch, and bycatch data using a maximum likelihood approach to estimate abundance, recruitment, and catchabilities, catches and bycatch of the commercial pot fisheries and groundfish trawl fisheries. A full model description is provided in Appendix A.

b-f. See appendix.

g. Critical assumptions of the model:

i. The base natural mortality is constant over shell condition and length and was estimated assuming a maximum age of 25 and applying the 1% rule (Zheng 2005).

ii. Survey and fisheries selectivities are a function of length and were constant over shell condition. Selectivities are a function of sex except for trawl bycatch selectivities, which are the same for both sexes. Four different survey selectivities were estimated: (1) 1968-69 (surveys at different times), (2) 1970-72 (surveys without a footrope chain), (3) 1973-1981, and (4) 1982-2010 (modifying approaches to surveys).

iii. Growth is a function of length and did not change over time for males. For females, three growth increments per molt as a function of length were estimated based on sizes at maturity (1968-1982, 1983-1993, and 1994-2010). Once mature, female red king crabs grow with a much smaller growth increment per molt.

iv. Molting probabilities are an inverse logistic function of length for males. Females molt annually.

v. Annual fishing seasons for the directed fishery are short.

vi. Survey catchability (Q) was estimated to be 0.896, based on a trawl experiment by Weinberg et al. (2004). Q was assumed to be constant over time except during 1970-1972. Q during 1970-1972 was estimated in the model.

vii. Males mature at sizes ≥120 mm CL. For convenience, female abundance was summarized at sizes ≥90 mm CL as an index of mature females.

viii. For summer trawl survey data, shell ages of newshell crabs were 12 months or less, and shell ages of oldshell and very oldshell crabs were more than 12 months.

ix. Measurement errors were assumed to be normally distributed for length compositions and were log-normally distributed for biomasses.

3. Model Selection and Evaluation

a. Alternative model configurations:

Eleven scenarios were compared for this report following September 2010 CPT request, the response to CIE review, and the response to the Stock Assessment Workshop recommendations.

Scenario 0: We called the base scenario as Scenario 0 and other scenarios as Scenarios 1-7. Scenario 0 is the original scenario 3 in the September 2010 SAFE report. The base scenario is: constant natural mortality (0.18), estimation of additional mortality for males during 1980-1984 (one parameter) and for females during 1976-1993 (one parameter for period 1980-1984 and another parameter for periods 1976-1979 and 1985-1993), and including the Bering Sea Fisheries Research Foundation (BSFRF) survey data.

Scenario 1: The same as scenario 0 except for using observed proportions in the variance formula for size composition.

Scenario 1a: The same as scenario 1 except estimating initial abundance by length and sex. An additional 36 parameters from scenario 1 are estimated. An additional likelihood component is added from the length compositions in the first year:

$$f = \sum_{l,sex}(observed\ length\ proportions - estimated\ length\ proportions)^2$$

Scenario 1b: The same as scenario 1 except only the standard survey data are used for estimating survey male and female abundances.

Scenario 1c: The same as scenario 1 except only the standard survey data are used for estimating survey male abundance and re-tow data are used for female abundance (the CPT option).

Scenario 2: The same as scenario 1 except for survey catchability for females changes annually. Specifically, an annual variable within the range, 0.8 to 1.0, is estimated within the model and multiplied by the fixed survey catchability of 0.896 for females. A penalty term with a CV of 0.1 is used to estimate this variable. This scenario illustrates the effects of annual variation on population and parameter estimates. Due to lack of data, it is difficult to estimate annual catchability. An additional 43 parameters from scenario 1 are estimated.

Scenario 3: The same as scenario 1 except for three levels of molting probabilities for males over time. The years grouped into three groups are from the results from the ADF&G stock assessment model (Zheng et al. 1995). Group 1 consists of 1968-79; group 2 consists of 1980-84, 1992-94, 1997, 1999, 2001, 2007-2010; and group 3 consists of 1985-91, 1995-96, 1998, 2000, and 2002-2006. Four additional parameters from scenario 1 are estimated.

Scenario 4: The same as scenario 1 except for replacing additional mortality parameters with assumed predation mortality. Predation moralities are assumed to occur on newshell crab only with the same predation mortality rate for both males and females. One parameter is predation mortality during 1980-1984 and the second parameter is for predation mortality during 1976-1979 and 1985-1993. Data is lacking for estimating predation mortalities. These two predation mortality rates are estimated in the model as two parameters. One less parameter from scenario 1 is estimated.

Scenario 5: Combination of scenarios 1, 2 and 3. An additional 47 parameters from scenario 1 are estimated.

Scenario 6: The same as scenario 3 except for assuming high bycatch rates before 1990. The average of the highest two observed bycatch rates during 1990-2006 from the directed pot and the average of top 2 bycatch rates from the Tanner crab fishery during 1991-1994 are used to estimate bycatch before 1990. This scenario assumes bycatch mortality rates before 1990 are equal to the high ends of bycatch rates estimated from the available observer data after 1990. Four additional parameters from scenario 1 are estimated.

Scenario 7: The same as scenario 3 except for estimating effective sample size (ESS) using observed sample sizes. Four additional parameters from scenario 1 are estimated. Effective sample sizes are estimated through two steps:

(1) Initial effective sample sizes are estimated as

$$n_y = \sum_l \hat{P}_{y,l}(1-\hat{P}_{y,l}) / \sum_l (P_{y,l} - \hat{P}_{y,l})^2$$

where $\hat{P}_{y,l}$ and $P_{y,l}$ is estimated and observed size compositions in year y and length group l, respectively.

(2) We assume n_y has a Beverton-Holt relationship with observed sample sizes, N_y:

$$n_y = N_y / (\alpha + \beta N_y)$$

where α and β are parameters. Different α and β parameter values are estimated for survey males, survey females, retained catch, male directed pot bycatch and female directed pot bycatch. Due to unreliable observed sample sizes for trawl bycatch, effective sample sizes are not estimated. Effective sample sizes are also not estimated for Tanner crab bycatch due to short observed time series.

b. Progression of results: NA.

c. Evidence of search for balance between realistic and simpler models: NA.

d. Convergence status/criteria: ADMB default convergence criteria.

e. Sample sizes for length composition data. Estimated sample sizes and effective sample sizes are summarized in tables.

f. Credible parameter estimates: all estimated parameters seem to be credible.

g. Model selection criteria. The likelihood values were used to select among alternatives that could be legitimately compared by that criterion.

h. Residual analysis. Residual plots are illustrated in figures.

i. Model evaluation is provided under Results, below.

4. Results

a. Effective sample sizes and weighting factors.

i. For scenario 0-6, we assumed constant effective sample sizes for the length/sex composition data. The sample sizes were compared with estimated effective sample sizes in Figure 7(0) for scenario 0. Estimated effective sample sizes were computed as:

$$n_y = \sum_l \hat{P}_{y,l}(1-\hat{P}_{y,l}) / \sum_l (P_{y,l} - \hat{P}_{y,l})^2$$

where $\hat{P}_{y,l}$ and $P_{y,l}$ is estimated and observed size compositions in year y and length group l, respectively. Estimated effective sample sizes vary greatly over time. For scenario 7, effective sample sizes are illustrated in Figure 7(7).

ii. Weights are assumed to be 500 for retained catch biomass, and 100 for all bycatch biomasses, 2 for recruitment variation, and 10 for recruitment sex ratio.

b. Tables of estimates.

i. Parameter estimates for scenario 0 are summarized in Tables 5 and 6.

ii. Abundance and biomass time series are provided in Table 7 for scenarios 0 and 7.

iii. Recruitment time series for scenario 0 are provided in Table 6.

iv. Time series of catch/biomass are provided in Tables 1 and 4.

Negative log-likelihood values and parameter estimates are summarized in Tables 5 and 6, respectively. Length-specific fishing mortality is equal to its selectivity times the full fishing mortality. Estimated full pot fishing mortalities for females and full fishing mortalities for trawl bycatch were very low due to low bycatch as well as handling mortality rates less than 1.0. Estimated recruits varied greatly from year to year (Table 6). Estimated low selectivities for male pot bycatch, relative to the retained catch, reflected the 20% handling mortality rate (Figure 8). Both selectivities were applied to the same level of full fishing mortality. Estimated selectivities for female pot bycatch were close to 1.0 for all mature females, and the estimated full fishing mortalities for female pot bycatch were lower than for male retained catch and bycatch (Table 6).

c. Graphs of estimates.

   i. Selectivities and molting probabilities by length are provided in Figures 8 and 9 for scenario 0.

      One of the most important results is estimated trawl survey selectivity/catchability (Figure 8). Survey selectivity affects not only the fitting of the data but also the absolute abundance estimates. Estimated survey selectivities in Figure 8 are generally smaller than the capture probabilities in Figure A1 because survey selectivities include capture probabilities and crab availability. NMFS survey catchability was estimated to be 0.896 from the trawl experiment and higher than that estimated from the BSFRF surveys (0.854). The reliability of estimated survey selectivities will greatly affect the application of the model to fisheries management. Under- or overestimates of survey selectivities will cause a systematic upward or downward bias of abundance estimates. Information about crab availability to the survey area at survey times will help estimate the survey selectivities.

      For scenario 0, estimated molting probabilities during 1968-2010 (Figure 9) were generally lower than those estimated from the 1954-1961 and 1966-1969 tagging data (Balsiger 1974). Lower molting probabilities mean more oldshell crab, possibly due to changes in molting probabilities over time or shell aging errors. Overestimates or underestimates of oldshell crabs will result in lower or higher estimates of male molting probabilities.

   ii. Estimated total survey biomass and mature male and female abundances are plotted in Figure 10.

      Estimated survey biomass, mature male and female abundances are similar between the assessment made in 2009 and 2010 (Figure 10a). Estimated biomass and mature abundances are lower during the late 1970s for scenario 3-7 than scenarios 0-2 (Figure 10a).

      The model did not fit the mature crab abundance directly and depicted the trends of the mature abundance well (Figure 10b). Estimated mature crab abundance increased dramatically in the mid 1970s then decreased precipitously in the early 1980s. Estimated mature crab abundance has increased during the last 20 years with mature females being 4.4 times more abundant in 2010 than in 1985 and mature males being 2.8 times more abundant in 2010 than in 1985 (Figure 10b).

   iii. Estimated recruitment time series are plotted in Figure 11 for scenario 0.

   iv. Estimated harvest rates are plotted against mature male biomass in Figure 12 for scenario 0.

      The average of estimated male recruits from 1995 to 2010 (Figure 11) and mature male biomass per recruit were used to estimate $B_{35\%}$. Alternative periods of 1968-present and 1985-present were compared in our previous report. The full fishing mortalities for the directed pot fishery at the time of fishing were plotted against mature male biomass on Feb. 15 (Figure 12). Before the current harvest strategy was adopted in 1996, many fishing mortalities were above $F_{35\%}$ (Figure 12). Under the current harvest strategy, estimated fishing mortalities were at or above the $F_{35\%}$ limits in 1998, 2005, 2007 and 2008 but below the $F_{35\%}$ limits in the other post-1995 years.

Estimated full pot fishing mortalities ranged from 0.00 to 1.07 during 1968-2009, with estimated values over 0.40 during 1968-1981, 1986-1987, 1990-1991, 1993, and 1998 (Table 6, Figure 12). Estimated fishing mortalities for pot female bycatch and trawl bycatch were generally less than 0.06.

v. Estimated mature male biomass and recruitment are plotted to illustrate their relationships with scenario 0 (Figure 13a). Annual stock productivities are illustrated in Figure 13b.

Stock productivity (recruitment/mature male biomass) was much higher before the 1976/1977 regime shift: the mean value was 1.857 during 1968-1977 and 0.356 during 1978-2010.

Egg clutch data collected during summer surveys may provide information about mature female reproductive conditions. Although egg clutch data are subject to rating errors as well as sampling errors, data trends over time may be useful. Proportions of empty clutches for newshell mature females >89 mm CL were high in some years before 1990, but have been low since 1990 (Figure 14). The highest proportion of empty clutches (0.2) was in 1986, and primarily involved soft shell females (shell condition 1). Clutch fullness fluctuated annually around average levels during two periods: before 1991 and after 1990 (Figure 14). The average clutch fullness was close for these two periods (Figure 14).

d. Graphic evaluation of the fit to the data.

i. Observed vs. estimated catches are plotted in Figure 15.

ii. Model fits to total survey biomass are shown in Figure 10 with a standardized residual plot in Figure 16.

iii. Model fits to catch and survey proportions by length are illustrated in Figures 17-24 and residual bubble plots are shown in Figures 25-27.

The model (scenario 0) fit the fishery biomass data well and the survey biomass reasonably well (Figures 10 and 15). Because the model estimates annual fishing mortality for pot male catch, pot female bycatch, and trawl bycatch, the deviations of observed and predicted (estimated) fishery biomass are mainly due to size composition differences.

The model also fit the length and shell composition data well (Figures 17-24). Model fit of length compositions in the trawl survey was better for newshell males and females than for oldshell males. The model predicted lower proportions of oldshell males in 1993, 1994, 2002, 2007 and 2008, and higher proportions of oldshell males in 1997, 2001, 2003, 2004, 2006 and 2010 than the area-swept estimates (Figure 18). In addition to size, molting probability may also be affected by age and environmental conditions. Tagging data show that molting probability changed over time (Balsiger 1974). Therefore, the relatively poor fit to oldshell males may be due to use of a constant molting probability function as well as shell aging errors. It is surprising that the model fit the length proportions of the pot male bycatch well with two simple linear selectivity functions (Figure 21). We explored a logistic selectivity function, but due to the long left tail of the pot male bycatch selectivity, the logistic selectivity function did not fit the data well.

Modal progressions are tracked well in the trawl survey data, particularly beginning in the mid-1990s (Figures 17 and 19). Cohorts first seen in the trawl survey data in 1975, 1986, 1990, 1995, 1999, 2002 and 2005 can be tracked over time. Some cohorts can be tracked over time in the pot bycatch as well (Figure 21), but the bycatch data did not track the cohorts as well as the survey data. Groundfish trawl bycatch data provide little information to track modal progression (Figures 23 and 24).

Standardized residuals of total survey biomass and proportions of length and shell condition are plotted to examine their patterns. Residuals were calculated as observed minus predicted and standardized by the estimated standard deviation. Standardized residuals of total survey biomass did not show any consistent patterns (Figure 16). Standardized residuals of proportions of survey newshell males appear to be random over length and year (Figure 25). Standardized residuals of proportions of survey oldshell males were mostly positive or negative for some years (Figure 26). This is expected since a constant molting probability function over time was used. Changes in molting probability over time or shell aging errors would create such residual patterns. There is an interesting pattern for residuals of proportions of survey females. Residuals were generally negative for large-sized mature females during 1969-1987 (Figure 27). Changes in growth over time or increased mortality may cause this pattern. The inadequacy of the model can be corrected by adding parameters to address these factors. Further study for female growth and availability for survey gears due to different molting times may be needed.

e. Retrospective and historic analyses.

Two kinds of retrospective analyses were conducted for this report: (1) historical results and (2) the 2010 model hindcast results. The historical results are the trajectories of biomass and abundance from previous assessments that capture both new data and changes in methodology over time. Treating the 2010 estimates as the baseline values, we can also evaluate how well the model had done in the past. The 2010 model results are based on sequentially excluding one-year of data to evaluate the current model performance with fewer data.

i. Retrospective analysis (retrospective bias in base model or models).

The performance of the 2010 model includes sequentially excluding one-year of data. The model with scenario 0 performed well during 2004-2009 (Figure 28).

Overall, both historical results and the 2010 model results performed reasonably well. No great overestimates or underestimates occurred as was observed in Pacific halibut (*Hippoglossus stenolepis*) (Parma 1993) or some eastern Bering Sea groundfish stocks (Zheng and Kruse 2002; Ianelli et al. 2003). Since the most recent model was not used to set TAC or overfishing limits until 2009, historical implications for management from the stock assessment errors cannot be evaluated at the current time. However, management implications of the ADF&G stock assessment model were evaluated by Zheng and Kruse (2002).

ii. Historic analysis (plot of actual estimates from current and previous assessments).

The model first fit the data from 1985 to 2004 in the terminal year of 2004. Thus, six historical assessment results are available. The main differences of the 2004 model were weighting factors and effective sample sizes for the likelihood functions. In 2004, the weighting factors were 1000 for survey biomass, 2000 for retained catch biomass and 200 for bycatch biomasses. The effective sample sizes were set to be 200 for all proportion data but weighting factors of 5, 2, and 1 were also applied to retained catch proportions, survey proportions and bycatch proportions. Estimates of time series of abundance in 2004 were generally higher than those estimated after 2004 (Figure 29).

In 2005, to improve the fit for retained catch data, the weight for retained catch biomass was increased to 3000 and the weight for retained catch proportions was increased to 6. All other weights were not changed. In 2006, all weights were re-configured. No weights were used for proportion data, and instead, effective sample sizes were set to 500 for retained catch, 200 for survey data, and 100 for bycatch data. Weights for biomasses were changed to 800 for retained catch, 300 for survey and 50 for bycatch. The weights in 2007 were the same as 2006. Generally, estimates of time series of abundance in 2005 were slightly lower than in 2006 and 2007, and there were few differences between estimates in 2006 and 2007 (Figure 29).

In 2008, estimated coefficients of variation for survey biomass were used to compute likelihood values as suggested by the CPT in 2007. Thus, weights were re-configured to: 500 for retained catch biomass, 50 for survey biomass, and 20 for bycatch biomasses. Effective sample size was lowered to 400 for the retained catch data. These changes were necessary for the estimation to converge and for a relatively good balanced fit to both biomasses and proportion data. Also, sizes at 50% selectivities for all fisheries data were allowed to change annually, subject to a random walk pattern, for all assessments before 2008. The 2008 model does not allow annual changes in any fishery selectivities. Except for higher estimates of abundance during the late 1980s and early 1990s, estimates of time series of abundance in 2008 were generally close to those in 2006 and 2007 (Figure 29).

In 2009 and 2010, the model was extended to the data through 1968. No weight factors were used for the NMFS survey biomass in 2009 and 2010 assessments.

f. Uncertainty and sensitivity analyses

i. Estimated standard deviations of parameters are summarized in Table 6 for scenario 0. Estimated standard deviations of mature male biomass are listed in Table 7.

ii. Likelihood profiles for mature male biomass, exploitable male abundance and exploitable male biomass in 2010 are illustrated in Figure 30 for scenario 0. The confidence intervals are quite narrow for all three values.

iii. Sensitivity analysis for handling mortality rate was reported in the SAFE report in May 2010. The baseline handling mortality rate for the directed pot fishery was set at 0.2. A 50% reduction and 100% increase resulted in 0.1 and 0.4 as alternatives. Overall, a higher handling mortality rate resulted in slightly higher estimates of mature abundance, and a lower rate resulted in a minor reduction of estimated mature abundance. Differences of estimated legal abundance and mature male biomass were small among these handling mortality rates.

iv. Sensitivity of weights. Sensitivity of weights was examined in the SAFE report in May 2010. Weights to biomasses (trawl survey biomass, retained catch biomass, and bycatch biomasses) were reduced to 50% or increased to 200% to examine their sensitivity to abundance estimates. Weights to the penalty terms (recruitment variation and sex ratio) were also reduced or increased. Overall, estimated biomasses were very close under different weights except during the mid-1970s.

The variation of estimated biomasses in the mid-1970s was mainly caused by the changes in estimates of additional mortalities in the early 1980s.

g. Comparison of alternative model scenarios

Estimating length proportions in the initial year (scenario 1a) results in mainly a better fit of survey length compositions at an expense of 36 more parameters than scenario 1 (Tables 5(1a) and 5(1)). Abundance and biomass estimates with scenario 1a are similar with scenario 1 that does not estimate initial length proportions (Figures 10a(1abc) and 10b(1abc)). Using only standard survey data (scenario 1b) results in a poorer fit of survey length compositions and biomass than scenarios using both standard and re-tow data (scenarios 1, 1a, and 1c) and has the lowest likelihood value (Tables 5(1b), 5(1), 5(1a) and 5(1c)). Although the likelihood value is higher for using both standard survey and re-tow data for males (scenario 1) than using only standard survey for males (scenario 1c), estimated abundances and biomasses are almost identical (Figures 10a(1abc) and 10b(1abc)). The higher likelihood value for scenario 1 over scenario 1c is due to trawl bycatch length compositions (Tables 5(1) and 5(1c)).

Scenario 7 statistically fits the data better than all other scenarios (Table 5). The biggest improvements of scenario 7 over other scenarios are better fitting the survey length compositions and retained catch biomass. Mature male abundance estimate with scenario 7 in 2008 falls into the 95% confidence interval of BSFRF survey estimates (Figure 10c (0&7)). Scenario 4 with model estimated predation mortalities during late 1970s and 1980s does not fit the data as well as the other scenarios (Table 5).

F. Calculation of the OFL and ABC

1. Bristol Bay RKC is currently placed in Tier 3 (NPFMC 2007).
2. For Tier 3 stocks, estimated biological reference points include $B_{35\%}$ and $F_{35\%}$. Estimated model parameters were used to conduct mature male biomass-per-recruit analysis.
3. Specification of the OFL:

The Tier 3 can be expressed by the following control rule:

a) $\frac{B}{B^*} > 1$ $\quad\quad F_{OFL} = F^*$

b) $\beta < \frac{B}{B^*} \le 1$ $\quad\quad F_{OFL} = F^*\left(\frac{B/B^* - \alpha}{1-\alpha}\right)$ $\quad\quad$ (1)

c) $\frac{B}{B^*} \le \beta$ $\quad\quad$ directed fishery $F = 0$ and $F_{OFL} \le F^*$

Where

B = a measure of the productive capacity of the stock such as spawning biomass or fertilized egg production. A proxy of B, MMB estimated at the time of primiparous female mating (February 15) is used as a default in the development of the control rule.

$F^* = F_{35\%}$, a proxy of F_{MSY}, which is a full selection instantaneous F that will produce MSY at the MSY producing biomass,

$B^* = B_{35\%}$, a proxy of B_{MSY}, which is the value of biomass at the MSY producing level,

β = a parameter with restriction that $0 \leq \beta < 1$. A default value of 0.25 is used.

α = a parameter with restriction that $0 \leq \alpha \leq \beta$. A default value of 0.1 is used.

Because trawl bycatch fishing mortality was not related to pot fishing mortality, average trawl bycatch fishing mortality during 1999 to 2009 was used for the per recruit analysis as well as for projections in the next section. Pot female bycatch fishing mortality was set equal to pot male fishing mortality times 0.02, an intermediate level during 1990-2009. Some discards of legal males occurred since the IFQ fishery started in 2005, but the discard rates were much lower during 2007-2009 than in 2005 after the fishing industry minimized discards of legal males. Thus, the average of retained selectivities and discard male selectivities during 2007-2009 were used to represent current trends for per recruit analysis and projections.

Average recruitments during three periods were used to estimate $B_{35\%}$: 1968-2010, 1985-2010, and 1995-2010 (Figure 11). Estimated $B_{35\%}$ is compared with historical mature male biomass in Figure 13a. We recommend using the average recruitment during 1995-present, which was used in 2008 and 2009 to set the overfishing limits. There are several reasons for supporting our recommendation. First, estimated recruitment was higher after 1994 than during 1985-1994 and there was a potential regime shift after 1989 (Overland et al. 1999), which corresponded to recruitment in 1995 and later. Second, recruitments estimated before 1985 came from a potentially higher natural mortality than we used to estimate $B_{35\%}$. Third, high recruitments during the late 1960s and 1970s generally occurred when the spawning stock was primarily located in the southern Bristol Bay, whereas the current spawning stock is mainly in the middle of Bristol Bay. The current flows favor larvae hatched in the southern Bristol Bay (see the section on Ecosystem Considerations). Stock productivity (recruitment/mature male biomass) was much higher before the 1976/1977 regime shift: the mean value was 1.857 during 1968-1977 and 0.356 during 1978-2004 (Figure 13).

The control rule is used for stock status determination. If total catch exceeds OFL estimated at *B*, then "overfishing" occurs. If *B* equals or declines below 0.5 B_{MSY} (i.e., MSST), the stock is "overfished." If *B* equals or declines below β*B_{MSY} or β*a proxy B_{MSY}, then the stock productivity is severely depleted and the fishery is closed.

The mcmc procedure is used to generate probability distribution for the OFL (only for scenario 7, Figure 31). The mean is very close to the median and is used for the OFL estimates. A P*=0.49 is used to estimate the ABC.

Specification of OFL: Values are in million lbs.

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch	OFL	ABC
2006/07			15.53	15.75	17.22	N/A	N/A
2007/08	44.8	85.9[A]	20.38	20.51	23.23	N/A	N/A
2008/09	37.6	87.8[B]	20.37	20.32	23.10	24.20	N/A
2009/10	34.3	89.0[C]	16.00	16.00	18.31	22.56	N/A
2010/11[0]		83.1[D]	NA	NA	NA	23.52	N/A
2010/11[7]		73.3[D]	NA	NA	NA	17.88	17.85

The stock was above MSST in 2009/10 and is hence not overfished. Overfishing did not occur during the 2009/10 fishing year. For 2010/2011, "0" is for scenario 0 and "7" is for scenario 7.

Notes:
A – Calculated from the assessment reviewed by the Crab Plan Team in September 2007
B – Calculated from the assessment reviewed by the Crab Plan Team in September 2008 and updated with 2008/09 catch
C – Calculated from the assessment reviewed by the Crab Plan Team in September 2009 and updated with 2009/10 catch
D – Calculated from the assessment reviewed by the Crab Plan Team in September 2010 and from the assessment in May 2011.

4. Based on the $B_{35\%}$ estimated from the average male recruitment during 1995-2010, the biological reference points were estimated as follows:

	Scenario 0	Scenario 7
$B_{35\%}$ =	62.696 million lbs, or 28,438 t	62.631 million lbs, or 28,409 t
$F_{35\%}$ =	0.32	0.32
$F_{40\%}$ =	0.26	0.26

Based on $B_{35\%}$ and $F_{35\%}$, the retained catch and total catch limits for 2010 were estimated to be:

	Scenario 0	Scenario 7
Retained catch:	21.287 million lbs, or 9,655.474 t,	15.606 mill.lbs, or 7,078.920 t
Total catch:	23.519 million lbs, or 10,667.863 t,	17.876 mill.lbs, or 8,108.230 t
MMB on 2/15/2011:	83.142 million lbs, or 37,712.4 t,	73.318 mill.lbs, or 33,256.50 t

Total catch includes retained catch and all other bycatch.

5. Based the OFL distributions, P*=0.49 results in 2010 ABC = 17.85 million lbs.

6. Alternative time periods of recruitment used to estimate $B_{35\%}$ for scenario 7:

Periods	$B_{35\%}$ (t)	MMB in 2010 Value(t)	%$B_{35\%}$	F	OFL (t)	Stock Status
1969-1984	118535.8	38418.3	32.4%	0.08	2307.5	Overfished, directed fishery closed
1969-2010	59834.9	36126.5	60.4%	0.18	4847.7	No overfished
1985-2010	23711.2	33256.5	140.3%	0.32	8108.2	No overfished
1995-2010	28408.9	33256.5	117.1%	0.32	8108.2	No overfished

The retained catch for 1969-1984 option is below the TAC threshold.

The productivities were much higher for brood year classes before the 1976/77 regime shift (Figure 13b). Recruitment levels were much higher from brood years before 1978 than after 1977 (Figure 11). The clutch fullness did not change much over time (Figure 14), which implies that mortalities from eggs to recruits had increased after the regime shift. Spatial distributions have also changed; high recruitments during the late 1960s and 1970s generally occurred when the spawning stock was primarily located in southern Bristol Bay while the current spawning stock is mainly in the middle of Bristol Bay. The current flows favor larvae hatched in southern Bristol Bay. If we believe that the productivity differences and differences of other population characteristics before 1978 were caused by fishing, not by the regime shift, then we should use the recruitment from 1969-1984 (corresponding to brood years before 1978) as the baseline to estimate $B_{35\%}$. If we believe that the regime shift during 1976/77 caused the productivity differences, then we should select the recruitments from period 1985-2010 or 1995-2010 as the baseline.

G. Rebuilding Analyses

NA.

H. Data Gaps and Research Priorities

1. The following data gaps exist for this stock:

   a. Information about changes in natural mortality in the early 1980s;

   b. Un-observed trawl bycatch in the early 1980s;

   c. Natural mortality;

   d. Crab availability to the trawl surveys;

   e. Juvenile crab abundance.

2. Research priorities:

   a. Estimating natural mortality;

   b. Estimating crab availability to the trawl surveys;

   c. Surveying juvenile crab abundance in near shore;

   d. Studying environmental factors that affect the survival rates from larvae to recruitment.

I. Projections and Future Outlook

1. Projections

Future population projections primarily depend on future recruitment, but crab recruitment is difficult to predict. Therefore, annual recruitment for the projections was a random selection from estimated recruitments during 1995-2010. Besides recruitment, the other major uncertainty for the projections is estimated abundance in 2010. The 2010 abundance was randomly selected from the estimated normal distribution of the assessment model output for each replicate. Three scenarios of fishing mortality for the directed pot fishery were used in the projections:

(1) No directed fishery. This was used as a base projection.

(2) $F_{40\%}$. This fishing mortality creates a buffer between the limits and target levels.

(3) $F_{35\%}$. This is the maximum fishing mortality allowed under the current overfishing definitions.

Each scenario was replicated 1000 times and projections made over 10 years beginning in 2010 (Table 8).

As expected, projected mature male biomasses are much higher without the directed fishing mortality than under the other scenarios. At the end of 10 years, projected mature male biomass is above $B_{35\%}$ for the $F_{40\%}$ scenario and similar to $B_{35\%}$ for the $F_{35\%}$ scenario (Table 8; Figure 32). Projected retained catch for the $F_{35\%}$ scenario is higher than those for the $F_{40\%}$ scenario (Table 8, Figure 33). Due to the poor recruitment during recent years, the projected biomass and retained catch are expected to decline during the next few years.

2. Near Future Outlook

The near future outlook for the Bristol Bay RKC stock is a starting declining trend. The three recent above-average year classes (hatching years 1990, 1994, and 1997) had entered the legal population by 2006 (Figure 34). Most individuals from the 1997 year class will continue to gain weight to offset loss of the legal biomass to fishing and natural mortalities. The above-average year class (hatching year 2000) with lengths centered around 87.5 mm CL for both males and females in 2006 and with lengths centered around 112.5-117.5 mm CL for males and around 107.5 mm CL for females in 2008 has largely entered the mature male population in 2009 and will continue to recruit to the legal population next year (Figure 34). However, no strong cohorts have been observed in the survey data after this cohort (Figure 34). Due to lack of recruitment, mature and legal crabs should decline next year. Current crab abundance is still low relative to the late 1970s, and without favorable environmental conditions, recovery to the high levels of the late 1970s is unlikely.

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Table 1. Bristol Bay red king crab annual catch and bycatch mortality biomass (million lbs) from June 1 to May 31. A handling mortality rate of 20% for pot and 80% for trawl was assumed to estimate bycatch mortality biomass.

	Retained Catch				Pot Bycatch		Trawl	Total
Year	U.S.	Cost-recovery	Foreign	Total	Males	Females	Bycatch	Catch
1960	0.600		26.898	27.498				27.498
1961	0.427		44.592	45.019				45.019
1962	0.068		54.275	54.343				54.343
1963	0.653		54.963	55.616				55.616
1964	0.823		58.170	58.993				58.993
1965	1.429		41.294	42.723				43.410
1966	0.997		42.356	43.353				44.732
1967	3.102		33.636	36.738				38.430
1968	8.686		27.469	36.155				34.523
1969	10.403		14.383	24.786				24.463
1970	8.559		12.984	21.543				20.516
1971	12.946		6.134	19.080				20.459
1972	21.745		4.720	26.465				27.296
1973	26.914		0.228	27.142				24.167
1974	42.266		0.476	42.742				42.742
1975	51.326		0.000	51.326				51.326
1976	63.920		0.000	63.920			1.426	65.346
1977	69.968		0.000	69.968			2.685	72.653
1978	87.618		0.000	87.618			2.757	90.375
1979	107.828		0.000	107.828			2.783	110.611
1980	129.948		0.000	129.948			2.135	132.083
1981	33.591		0.000	33.591			0.448	34.039
1982	3.001		0.000	3.001			1.201	4.202
1983	0.000		0.000	0.000			0.885	0.885
1984	4.182		0.000	4.182			2.316	6.498
1985	4.175		0.000	4.175			0.829	5.004
1986	11.394		0.000	11.394			0.432	11.825
1987	12.289		0.000	12.289			0.311	12.600
1988	7.388		0.000	7.388			1.174	8.561
1989	10.265		0.000	10.265			0.374	10.638
1990	20.362	0.081	0.000	20.443	1.139	1.154	0.501	23.237
1991	17.178	0.206	0.000	17.384	0.881	0.142	0.576	18.982
1992	8.043	0.074	0.000	8.117	1.191	0.780	0.571	10.659
1993	14.629	0.053	0.000	14.682	1.649	1.133	0.836	18.300
1994	0.000	0.093	0.000	0.093	0.000	0.000	0.180	0.274
1995	0.000	0.080	0.000	0.080	0.000	0.000	0.213	0.293
1996	8.406	0.108	0.000	8.514	0.356	0.002	0.238	9.109
1997	8.756	0.155	0.000	8.911	0.528	0.034	0.168	9.641
1998	14.757	0.188	0.000	14.946	2.074	1.547	0.355	18.922
1999	11.670	0.186	0.000	11.856	0.679	0.015	0.408	12.958
2000	8.154	0.086	0.000	8.241	0.779	0.078	0.230	9.328
2001	8.403	0.120	0.000	8.523	0.902	0.309	0.330	10.065
2002	9.570	0.096	0.000	9.666	0.956	0.013	0.245	10.881
2003	15.697	0.034	0.000	15.731	1.945	0.709	0.298	18.682
2004	15.245	0.202	0.000	15.447	0.746	0.338	0.277	16.807
2005	18.309	0.209	0.000	18.518	2.923	0.879	0.403	22.723
2006	15.444	0.304	0.000	15.748	1.199	0.067	0.205	17.220
2007	20.366	0.146	0.000	20.512	2.150	0.330	0.233	23.225
2008	20.318	0.000	0.000	20.318	2.518	0.264	0.334	23.100
2009	15.933	0.100	0.000	16.033	1.910	0.149	0.218	18.310

Table 2. Comparison of GHL/TAC and actual catch (million lbs) of Bristol Bay red king crab.

	GHL		Actual		
Year	Range	Mid-point	Catch	Rel.Error	%Rel.Error
1980	70-120	95.00	129.95	34.95	36.79
1981	70-100	85.00	33.59	-51.41	-60.48
1982	10-20	15.00	3.00	-12.00	-79.99
1983	0	0.00	0.00	NA	NA
1984	2.5-6	4.25	4.18	-0.07	-1.59
1985	3-5	4.00	4.18	0.18	4.38
1986	6-13	9.50	11.39	1.89	19.94
1987	8.5-17.7	13.10	12.29	-0.81	-6.19
1988		7.50	7.39	-0.11	-1.50
1989		16.50	10.26	-6.24	-37.79
1990		17.10	20.36	3.26	19.08
1991		18.00	17.18	-0.82	-4.57
1992		10.30	8.04	-2.26	-21.91
1993		16.80	14.63	-2.17	-12.93
1994		0.00	0.00	0.00	
1995		0.00	0.00	0.00	
1996		5.00	8.41	3.41	68.11
1997		7.00	8.76	1.76	25.09
1998		16.40	14.76	-1.64	-10.02
1999		10.66	11.67	1.01	9.48
2000		8.35	8.15	-0.20	-2.34
2001		7.15	8.40	1.25	17.52
2002		9.27	9.57	0.30	3.24
2003		15.71	15.70	-0.01	-0.08
2004		15.40	15.25	-0.15	-1.00
2005		18.33	18.31	-0.02	-0.11
2006		15.53	15.44	-0.08	-0.53
2007		20.38	20.37	-0.02	-0.08
Total		461.23	431.38	-29.85	-6.47

Table 3. Annual sample sizes for catch by length and shell condition for retained catch and bycatch of Bristol Bay red king crab.

	Trawl Survey		Retained	Pot Bycatch		Trawl Bycatch	
Year	Males	Females	Catch	Males	Females	Males	Females
1968	3,684	2,165	18,044				
1969	6,144	4,992	22,812				
1970	1,546	1,216	3,394				
1971			10,340				
1972	1,106	767	15,046				
1973	1,783	1,888	11,848				
1974	2,505	1,800	27,067				
1975	2,943	2,139	29,570				
1976	4,724	2,956	26,450			2,327	676
1977	3,636	4,178	32,596			14,014	689
1978	4,132	3,948	27,529			8,983	1,456
1979	5,807	4,663	27,900			7,228	2,821
1980	2,412	1,387	34,747			47,463	39,689
1981	3,478	4,097	18,029			42,172	49,634
1982	2,063	2,051	11,466			84,240	47,229
1983	1,524	944	0			204,464	104,910
1984	2,679	1,942	4,404			357,981	147,134
1985	792	415	4,582			169,767	30,693
1986	1,962	367	5,773			62,023	20,800
1987	1,168	1,018	4,230			60,606	32,734
1988	1,834	546	9,833			102,037	57,564
1989	1,257	550	32,858			47,905	17,355
1990	858	603	7,218	873	699	5,876	2,665
1991	1,378	491	36,820	1,801	375	2,964	962
1992	513	360	23,552	3,248	2,389	1,157	2,678
1993	1,009	534	32,777	5,803	5,942		
1994	443	266	0	0	0	4,953	3,341
1995	2,154	1,718	0	0	0	1,729	6,006
1996	835	816	8,896	230	11	24,583	9,373
1997	1,282	707	15,747	4,102	906	9,035	5,759
1998	1,097	1,150	16,131	11,079	9,130	25,051	9,594
1999	820	540	17,666	1,048	36	16,653	5,187
2000	1,278	1,225	14,091	8,970	1,486	36,972	10,673
2001	611	743	12,854	9,102	4,567	56,070	32,745
2002	1,032	896	15,932	9,943	302	27,705	25,425
2003	1,669	1,311	16,212	17,998	10,327	281	307
2004	2,871	1,599	20,038	8,258	4,112	137	120
2005	1,283	1,682	21,938	55,019	26,775	186	124
2006	2,321	2,672	18,027	29,383	3,594	217	168
2007	2,252	2,499	22,387	58,097	12,411	1,981	2,880
2008	2,362	3,352	14,567	49,315	8,488	1,013	673
2009	1,385	1,857	16,708	50,017	6,024		
2010	1,344	1,633					

Table 4. Annual catch (million crabs) and catch per unit effort of the Bristol Bay red king crab fishery.

	Japanese Tanglenet		Russian Tanglenet		U.S. Pot/trawl		Standardized
Year	Catch	Crabs/tan	Catch	Crabs/tan	Catch	Crabs/potlift	Crabs/tan
1960	1.949	15.2	1.995	10.4	0.088		15.8
1961	3.031	11.8	3.441	8.9	0.062		12.9
1962	4.951	11.3	3.019	7.2	0.010		11.3
1963	5.476	8.5	3.019	5.6	0.101		8.6
1964	5.895	9.2	2.800	4.6	0.123		8.5
1965	4.216	9.3	2.226	3.6	0.223		7.7
1966	4.206	9.4	2.560	4.1	0.140	52	8.1
1967	3.764	8.3	1.592	2.4	0.397	37	6.3
1968	3.853	7.5	0.549	2.3	1.278	27	7.8
1969	2.073	7.2	0.369	1.5	1.749	18	5.6
1970	2.080	7.3	0.320	1.4	1.683	17	5.6
1971	0.886	6.7	0.265	1.3	2.405	20	5.8
1972	0.874	6.7			3.994	19	
1973	0.228				4.826	25	
1974	0.476				7.710	36	
1975					8.745	43	
1976					10.603	33	
1977					11.733	26	
1978					14.746	36	
1979					16.809	53	
1980					20.845	37	
1981					5.308	10	
1982					0.541	4	
1983					0.000		
1984					0.794	7	
1985					0.796	9	
1986					2.100	12	
1987					2.122	10	
1988					1.236	8	
1989					1.685	8	
1990					3.130	12	
1991					2.661	12	
1992					1.208	6	
1993					2.270	9	
1994					0.015		
1995					0.014		
1996					1.264	16	
1997					1.338	15	
1998					2.238	15	
1999					1.923	12	
2000					1.272	12	
2001					1.287	19	
2002					1.484	20	
2003					2.510	18	
2004					2.272	23	
2005					2.763	30	
2006					2.477	31	
2007					3.131	28	
2008					3.064	22	
2009					2.553	21	

Table 5(0). Summary of statistics for the model (Scenario 0).

Parameter counts

Fixed growth parameters	9
Fixed recruitment parameters	2
Fixed length-weight relationship parameters	6
Fixed mortality parameters	4
Fixed survey catchability parameter	1
Fixed high grading parameters	5
Fixed initial (1968) length composition parameters	56
Total number of fixed parameters	83
Free growth parameters	4
Initial abundance (1968)	1
Recruitment-distribution parameters	2
Mean recruitment parameters	1
Male recruitment deviations	43
Female recruitment deviations	43
Natural and fishing mortality parameters	4
Survey catchability parameters	2
Pot male fishing mortality deviations	44
Bycatch mortality from the Tanner crab fishery	6
Pot female bycatch fishing mortality deviations	22
Trawl bycatch fishing mortality deviations	36
Free selectivity parameters	28
Total number of free parameters	236
Total number of fixed and free parameters	319

Negative log likelihood components

Length compositions---retained catch	-1024.680
Length compositions---pot male discard	-760.741
Length compositions---pot female discard	-1963.540
Length compositions---survey	-51723.100
Length compositions---trawl discard	-1699.290
Length compositions---Tanner crab discards	-161.881
Pot discard male biomass	163.488
Retained catch biomass	48.618
Pot discard female biomass	0.126
Trawl discard	7.989
Survey biomass	75.092
Recruitment variation	163.725
Sex ratio of recruitment	0.060
Total	-56870.600

Table 5(1). Summary of statistics for the model (Scenario 1).

Total number of free parameters	236
Total number of fixed and free parameters	319
Negative log likelihood components	
Length compositions---retained catch	-1030.190
Length compositions---pot male discard	-776.469
Length compositions---pot female discard	-1945.150
Length compositions---survey	-52032.000
Length compositions---trawl discard	-1708.630
Length compositions---Tanner crab discards	-229.562
Pot discard male biomass	190.329
Retained catch biomass	57.222
Pot discard female biomass	0.116
Trawl discard	9.545
Survey biomass	82.103
Recruitment variation	128.772
Sex ratio of recruitment	0.096
Total	-57253.500

Table 5(1a). Summary of statistics for the model (Scenario 1a).

Total number of free parameters	272
Total number of fixed and free parameters	319
Negative log likelihood components	
Length compositions---retained catch	-1049.000
Length compositions---pot male discard	-776.671
Length compositions---pot female discard	-1947.330
Length compositions---survey	-52065.300
Length compositions---trawl discard	-1707.970
Length compositions---Tanner crab discards	-229.256
Pot discard male biomass	190.117
Retained catch biomass	55.897
Pot discard female biomass	0.116
Trawl discard	9.507
Survey biomass	79.610
Recruitment variation	124.157
Sex ratio of recruitment	0.063
Total	-57315.800

Table 5(1b). Summary of statistics for the model (Scenario 1b).

Total number of free parameters	236
Total number of fixed and free parameters	319
Negative log likelihood components	
Length compositions---retained catch	-1030.110
Length compositions---pot male discard	-770.865
Length compositions---pot female discard	-1939.970
Length compositions---survey	-51722.400
Length compositions---trawl discard	-1699.340
Length compositions---Tanner crab discards	-190.755
Pot discard male biomass	189.517
Retained catch biomass	60.297
Pot discard female biomass	0.148
Trawl discard	10.826
Survey biomass	114.736
Recruitment variation	126.910
Sex ratio of recruitment	0.087
Total	-56850.500

Table 5(1c). Summary of statistics for the model (Scenario 1c).

Total number of free parameters	236
Total number of fixed and free parameters	319
Negative log likelihood components	
Length compositions---retained catch	-1031.810
Length compositions---pot male discard	-777.163
Length compositions---pot female discard	-1945.450
Length compositions---survey	-51999.200
Length compositions---trawl discard	-1708.710
Length compositions---Tanner crab discards	-229.475
Pot discard male biomass	193.475
Retained catch biomass	57.673
Pot discard female biomass	0.148
Trawl discard	10.408
Survey biomass	82.023
Recruitment variation	120.245
Sex ratio of recruitment	0.075
Total	-57217.400

Table 5(2). Summary of statistics for the model (Scenario 2).

Total number of free parameters	279
Total number of fixed and free parameters	362
Negative log likelihood components	
Length compositions---retained catch	-1032.700
Length compositions---pot male discard	-775.437
Length compositions---pot female discard	-1942.770
Length compositions---survey	-52257.600
Length compositions---trawl discard	-1714.620
Length compositions---Tanner crab discards	-229.541
Pot discard male biomass	186.884
Retained catch biomass	54.766
Pot discard female biomass	0.065
Trawl discard	10.124
Survey biomass	66.198
Recruitment variation	130.957
Sex ratio of recruitment	0.191
Total	-57475.300

Table 5(3). Summary of statistics for the model (Scenario 3).

Total number of free parameters	240
Total number of fixed and free parameters	323
Negative log likelihood components	
Length compositions---retained catch	-1071.690
Length compositions---pot male discard	-774.732
Length compositions---pot female discard	-1949.400
Length compositions---survey	-52160.700
Length compositions---trawl discard	-1709.570
Length compositions---Tanner crab discards	-191.088
Pot discard male biomass	182.839
Retained catch biomass	50.086
Pot discard female biomass	0.190
Trawl discard	18.820
Survey biomass	70.458
Recruitment variation	122.903
Sex ratio of recruitment	0.061
Total	-57411.500

Table 5(4). Summary of statistics for the model (Scenario 4).

Total number of free parameters	235
Total number of fixed and free parameters	318
Negative log likelihood components	
Length compositions---retained catch	-1011.540
Length compositions---pot male discard	-774.676
Length compositions---pot female discard	-1942.280
Length compositions---survey	-51861.700
Length compositions---trawl discard	-1704.580
Length compositions---Tanner crab discards	-228.792
Pot discard male biomass	184.894
Retained catch biomass	81.026
Pot discard female biomass	0.293
Trawl discard	0.201
Survey biomass	70.560
Recruitment variation	144.984
Sex ratio of recruitment	0.003
Total	-57040.700

Table 5(5). Summary of statistics for the model (Scenario 5).

Total number of free parameters	283
Total number of fixed and free parameters	366
Negative log likelihood components	
Length compositions---retained catch	-1074.680
Length compositions---pot male discard	-773.922
Length compositions---pot female discard	-1946.390
Length compositions---survey	-52393.300
Length compositions---trawl discard	-1714.850
Length compositions---Tanner crab discards	-191.197
Pot discard male biomass	181.482
Retained catch biomass	48.092
Pot discard female biomass	0.096
Trawl discard	19.464
Survey biomass	60.417
Recruitment variation	123.303
Sex ratio of recruitment	0.147
Total	-57632.300

Table 5(6). Summary of statistics for the model (Scenario 6).

Total number of free parameters	240
Total number of fixed and free parameters	323
Negative log likelihood components	
Length compositions---retained catch	-1067.170
Length compositions---pot male discard	-774.910
Length compositions---pot female discard	-1953.360
Length compositions---survey	-52168.300
Length compositions---trawl discard	-1707.460
Length compositions---Tanner crab discards	-133.085
Pot discard male biomass	183.693
Retained catch biomass	49.541
Pot discard female biomass	0.163
Trawl discard	19.401
Survey biomass	74.087
Recruitment variation	117.985
Sex ratio of recruitment	0.009
Total	-57455.400

Table 5(7). Summary of statistics for the model (Scenario 7).

Total number of free parameters	250
Total number of fixed and free parameters	333
Negative log likelihood components	
Length compositions---retained catch	-1041.000
Length compositions---pot male discard	-766.206
Length compositions---pot female discard	-1980.340
Length compositions---survey	-52815.000
Length compositions---trawl discard	-1699.890
Length compositions---Tanner crab discards	-189.834
Pot discard male biomass	170.221
Retained catch biomass	11.402
Pot discard female biomass	0.420
Trawl discard	22.085
Survey biomass	69.413
Recruitment variation	140.423
Sex ratio of recruitment	0.003
Total	-58032.000

Table 6(0). Summary of model parameter estimates (scenario 0) for Bristol Bay red king crab. Estimated values and standard deviations. All values are on a log scale. Male recruit is exp(mean+males), and female recruit is exp(mean+males+females).

	Recruits				F for Directed Pot Fishery				F for Trawl	
Year	Females	S. dev.	Males	S.dev.	Males	S.dev.	Females	S.dev.	Est.	S.dev.
Mean	16.189	0.022	16.189	0.022	-2.040	0.033	0.011	0.001	-4.682	0.074
1968					2.099	0.011				
1969	-0.293	0.110	0.968	0.066	2.078	0.059				
1970	0.604	0.116	0.919	0.098	1.798	0.062				
1971	-0.348	0.099	2.081	0.051	1.478	0.066				
1972	0.718	0.224	0.065	0.174	1.545	0.069				
1973	-0.489	0.119	1.600	0.057	1.297	0.073				
1974	0.192	0.091	1.582	0.059	1.486	0.069				
1975	0.301	0.061	2.494	0.046	1.331	0.064				
1976	-0.298	0.243	0.699	0.128	1.412	0.066			-0.293	0.080
1977	0.600	0.167	0.517	0.122	1.488	0.066			0.258	0.078
1978	0.572	0.134	0.967	0.098	1.630	0.057			0.179	0.077
1979	0.279	0.131	1.281	0.095	1.692	0.045			0.140	0.077
1980	-0.019	0.123	1.536	0.098	2.099	0.003			0.096	0.077
1981	0.254	0.087	1.266	0.079	1.769	0.061			-0.547	0.076
1982	-0.170	0.046	2.176	0.048	-0.193	0.060			1.105	0.080
1983	-0.226	0.081	1.179	0.054	-10.089	0.415			1.107	0.079
1984	0.174	0.064	1.111	0.044	0.714	0.059			2.000	0.002
1985	0.435	0.188	-1.422	0.143	0.877	0.060			1.332	0.078
1986	0.317	0.061	0.351	0.046	1.523	0.057			0.318	0.077
1987	0.130	0.130	-0.435	0.084	1.232	0.053			-0.206	0.076
1988	-0.321	0.265	-1.509	0.163	0.361	0.048			0.969	0.075
1989	0.415	0.137	-0.786	0.107	0.499	0.046			-0.348	0.075
1990	-0.209	0.096	0.109	0.062	1.148	0.043	1.851	0.112	-0.115	0.075
1991	-0.192	0.115	-0.521	0.075	1.129	0.045	-0.274	0.112	0.126	0.075
1992	-0.167	0.355	-2.494	0.228	0.618	0.046	2.000	0.028	0.246	0.076
1993	-0.360	0.095	-0.578	0.056	1.283	0.049	1.825	0.112	0.649	0.075
1994	-0.247	0.400	-2.746	0.242	-10.535	0.407	1.175	5.438	-0.783	0.076
1995	-0.008	0.037	0.952	0.034	-10.789	0.407	1.376	4.903	-0.787	0.076
1996	-0.016	0.104	-0.453	0.072	0.309	0.043	-3.798	0.170	-0.805	0.076
1997	-0.722	0.407	-2.807	0.245	0.434	0.043	-1.258	0.116	-1.155	0.076
1998	-0.210	0.105	-0.446	0.064	1.143	0.045	1.856	0.114	-0.441	0.074
1999	-0.104	0.060	0.582	0.043	0.696	0.045	-2.334	0.122	-0.303	0.074
2000	-0.053	0.176	-0.727	0.108	0.301	0.044	-0.402	0.117	-0.944	0.075
2001	1.036	0.191	-1.655	0.163	0.289	0.044	0.949	0.116	-0.646	0.075
2002	0.157	0.040	0.979	0.035	0.378	0.044	-2.327	0.124	-0.998	0.075
2003	-0.084	0.180	-0.813	0.116	0.883	0.043	1.025	0.117	-1.213	0.075
2004	0.170	0.091	0.235	0.077	0.712	0.044	0.301	0.117	-0.911	0.075
2005	0.192	0.048	0.927	0.045	1.115	0.046	0.756	0.118	-1.076	0.075
2006	-0.254	0.131	-0.026	0.084	0.800	0.047	-1.630	0.119	-1.163	0.076
2007	-0.474	0.181	-0.372	0.099	1.073	0.051	-0.353	0.119	-1.164	0.077
2008	0.164	0.250	-1.374	0.183	1.077	0.057	-0.549	0.120	-0.930	0.078
2009	-0.380	0.335	-1.670	0.204	0.730	0.061	-0.719	0.121	-1.293	0.081
2010	-0.532	0.393	-1.886	0.241						

Table 6(0) (continued). Summary of model parameter estimates for Bristol Bay red king crab. Estimated values and standard deviations.

Parameter	Value	St.dev.	Parameter	Value	St.dev.
Mm80-84	0.569	0.016	log_srv_L50, m, 70-72	5.200	0.000
Mf80-84	0.884	0.020	srv_slope, f, 70-72	0.146	0.010
Mf76-79,85-93	0.045	0.006	log_srv_L50, f, 70-72	4.387	0.014
log_betal, females	0.138	0.053	log_srv_L50, m, 73-81	4.391	0.028
log_betal, males	0.718	0.073	srv_slope, f, 73-81	0.064	0.003
log_betar, females	-0.365	0.068	log_srv_L50, f, 73-81	4.424	0.017
log_betar, males	-0.335	0.053	log_srv_L50, m, 82-10	4.558	0.028
Q, females, 70-72	0.172	0.018	srv_slope, f, 82-10	0.039	0.002
Q, males, 70-72	0.886	0.100	log_srv_L50, f, 82-10	4.547	0.019
Q, 68-69, 73-10	NA	NA	log_srv_L50, m, 68-69	4.508	0.015
moltp_slope	0.088	0.003	srv_slope, f, 68-69	0.019	0.002
log_moltp_L50	4.941	0.003	log_srv_L50, f, 68-69	5.037	0.071
log_N68	18.960	0.031	TC_slope, females	0.284	0.067
log_avg_L50, 73-10	4.926	0.001	log_TC_L50, females	4.539	0.013
log_avg_L50, 68-72	4.864	0.005	TC_slope, males	0.293	0.019
ret_fish_slope, 73-10	0.503	0.020	log_TC_L50, males	5.021	0.043
ret_fish_slope, 68-72	0.307	0.036	log_TC_F, males, 91	-2.861	0.358
pot disc.males, φ	-0.249	0.011	log_TC_F, males, 92	-4.027	0.333
pot disc.males, κ	0.003	0.000	log_TC_F, males, 93	-5.166	0.309
pot disc.males, γ	-0.012	0.000	log_TC_F, females, 91	-2.947	0.084
sel_62.5mm, 68-72	1.400	0.000	log_TC_F, females, 92	-4.134	0.084
post disc.fema., slope	0.470	0.195	log_TC_F, females, 93	-4.725	0.083
log_pot disc.fema., L50	4.401	0.012			
trawl disc slope	0.057	0.003			
log_trawl disc L50	5.031	0.048			

Table 7(0). Annual abundance estimates (million crabs), mature male biomass (MMB, million lbs), and total survey biomass estimates (million lbs) for red king crab in Bristol Bay estimated by length-based analysis (scenario 0) from 1968-2010. Mature male biomass for year *t* is on Feb. 15, year *t*+1. Size measurements are mm CL.

	Males				Females	Total Survey Biomass	
Year (t)	Mature (>119mm)	Legal (>134mm)	MMB (>119mm)	MMB SD	Mature (>89mm)	Model Est. (>64mm)	Area-swept (>64mm)
1968	14.773	8.689	33.703	1.295	61.581	176.441	176.524
1969	14.503	6.210	33.837	1.830	62.857	178.280	192.111
1970	17.576	6.847	45.325	2.626	65.774	79.067	94.888
1971	20.606	8.874	59.795	3.432	73.180	97.475	
1972	26.745	11.723	76.884	4.474	91.274	121.302	110.820
1973	33.557	14.826	103.474	5.369	108.613	417.730	351.646
1974	49.241	20.401	145.179	6.710	113.334	484.766	424.121
1975	54.551	27.731	168.948	7.802	119.765	586.663	461.200
1976	56.842	31.093	172.964	7.738	155.033	670.492	626.366
1977	64.331	32.001	189.935	7.195	194.575	713.718	800.168
1978	82.884	36.457	234.662	7.161	186.750	720.634	710.799
1979	83.895	44.393	232.561	8.315	168.172	690.285	536.477
1980	65.588	41.934	99.124	4.141	159.187	632.176	503.933
1981	24.693	14.940	44.738	2.819	65.212	282.425	247.233
1982	13.085	6.862	33.775	1.843	29.498	156.795	292.355
1983	9.907	5.152	27.494	1.282	18.805	117.909	104.135
1984	8.733	4.161	19.951	0.923	15.726	99.705	331.782
1985	8.807	3.268	28.594	1.076	11.696	69.820	72.763
1986	13.096	5.588	38.138	1.407	16.683	91.041	102.052
1987	15.668	7.354	49.152	1.635	20.592	101.798	145.811
1988	15.922	9.097	58.854	1.766	26.035	107.415	111.488
1989	17.105	10.482	64.528	1.822	25.202	113.963	129.489
1990	17.298	11.229	58.600	1.816	22.631	116.169	116.127
1991	14.003	9.919	47.843	1.758	22.284	105.958	182.621
1992	11.331	7.956	44.320	1.689	22.145	94.618	76.571
1993	12.050	7.407	39.575	1.649	19.790	91.933	103.969
1994	11.504	6.809	51.076	1.688	16.732	80.953	65.674
1995	11.847	8.505	56.662	1.646	15.885	96.183	79.206
1996	11.888	9.112	51.742	1.564	21.160	110.023	90.138
1997	11.310	8.129	47.997	1.510	30.669	115.611	174.149
1998	15.340	7.900	52.174	1.606	29.907	121.441	168.189
1999	17.133	9.196	62.369	1.818	26.272	123.444	123.648
2000	15.528	10.688	63.017	1.864	28.871	127.976	139.183
2001	14.653	10.467	61.300	1.818	32.709	132.544	104.985
2002	16.882	10.221	67.552	1.855	31.667	145.586	142.274
2003	17.768	11.332	65.713	1.908	38.098	154.810	192.746
2004	15.934	10.861	61.636	1.914	46.439	160.610	194.642
2005	18.736	10.455	64.130	2.075	46.567	176.779	212.034
2006	19.688	11.220	71.307	2.369	54.129	186.154	189.854
2007	20.602	12.332	70.825	2.740	61.516	197.810	206.408
2008	23.443	12.565	79.161	3.548	57.536	197.964	219.671
2009	24.430	14.109	88.969	4.392	51.098	190.795	178.893
2010	22.730	15.371	83.142	3.877	44.515	180.151	151.357

Table 7(7). Annual abundance estimates (million crabs), mature male biomass (MMB, million lbs), and total survey biomass estimates (million lbs) for red king crab in Bristol Bay estimated by length-based analysis (scenario 7) from 1968-2010. Mature male biomass for year *t* is on Feb. 15, year *t*+1. Size measurements are mm CL.

	Males				Females	Total Survey Biomass	
Year (t)	Mature (>119mm)	Legal (>134mm)	MMB (>119mm)	MMB SD	Mature (>89mm)	Model Est. (>64mm)	Area-swept (>64mm)
1968	13.395	7.855	28.462	1.595	48.455	158.920	176.524
1969	13.261	5.925	28.941	1.608	51.266	158.970	192.111
1970	15.607	6.749	38.915	2.466	55.849	80.419	94.888
1971	16.814	8.609	48.807	3.145	60.689	96.000	
1972	20.649	10.465	58.098	3.838	73.064	119.089	110.820
1973	26.809	12.515	80.319	4.720	88.236	332.788	351.646
1974	39.955	17.850	113.837	5.780	92.494	396.001	424.121
1975	45.302	24.825	137.271	6.374	98.762	482.111	461.200
1976	49.171	28.309	147.549	6.315	125.484	557.313	626.366
1977	57.923	30.245	170.739	6.087	153.753	601.763	800.168
1978	74.783	36.363	215.284	6.073	148.817	621.373	710.799
1979	76.172	45.520	214.615	6.133	137.068	608.837	536.477
1980	59.768	42.512	83.435	2.761	130.618	562.847	503.933
1981	20.627	11.045	31.180	1.119	54.321	231.461	247.233
1982	10.767	4.236	24.891	0.788	24.366	128.037	292.355
1983	8.473	3.451	21.619	0.629	15.818	101.999	104.135
1984	7.498	2.996	15.361	0.534	15.032	91.800	331.782
1985	7.713	2.284	22.474	0.721	12.299	66.930	72.763
1986	12.946	4.891	34.727	1.097	17.906	91.331	102.052
1987	16.365	7.239	50.071	1.413	21.531	104.651	145.811
1988	17.045	9.755	63.252	1.601	26.699	113.856	111.488
1989	18.599	11.606	71.655	1.691	25.644	122.245	129.489
1990	19.045	12.686	67.569	1.691	22.608	125.274	116.127
1991	15.680	11.539	56.218	1.651	21.138	114.746	182.621
1992	12.406	9.305	51.577	1.574	21.200	102.057	76.571
1993	12.563	7.833	42.588	1.400	18.998	95.003	103.969
1994	11.822	6.546	51.346	1.374	16.087	81.469	65.674
1995	12.219	7.803	55.161	1.307	15.592	93.888	79.206
1996	12.473	9.337	53.114	1.294	21.635	110.511	90.138
1997	11.955	8.638	50.879	1.287	31.617	119.200	174.149
1998	15.650	7.876	52.810	1.330	29.920	122.631	168.189
1999	17.942	9.746	65.697	1.528	26.456	126.053	123.648
2000	15.759	9.977	61.644	1.460	29.000	126.188	139.183
2001	15.084	10.676	62.513	1.483	33.254	134.131	104.985
2002	16.264	9.752	63.298	1.469	33.455	142.740	142.274
2003	17.461	11.105	63.808	1.566	40.292	155.679	192.746
2004	16.078	10.909	62.042	1.644	48.833	162.743	194.642
2005	19.401	10.793	67.066	1.917	47.635	178.517	212.034
2006	20.394	12.031	75.448	2.301	53.662	188.350	189.854
2007	20.391	13.203	72.657	2.672	62.258	200.812	206.408
2008	21.374	11.409	70.642	3.086	58.798	195.299	219.671
2009	22.154	11.148	75.197	3.717	53.266	185.127	178.893
2010	21.191	11.719	73.318	3.407	47.509	173.627	151.357

Table 8(0). Comparison of projected mature male biomass (million lbs) on Feb. 15, retained catch (million lbs), their 95% limits, and mean fishing mortality with no directed fishery, $F_{40\%}$, and $F_{35\%}$ harvest strategy with $F_{35\%}$ constraint during 2010-2019. Parameter estimates with scenario 0 are used for the projection.

Year	MMB	95% limits of MMB		Catch	95% limits of catch	
No directed fishery						
2010	104.218	96.292	111.677	0	0	0
2011	108.824	100.547	116.612	0	0	0
2012	105.905	97.845	113.481	0	0	0
2013	100.253	92.339	107.955	0	0	0
2014	99.470	86.880	118.797	0	0	0
2015	104.726	81.062	144.500	0	0	0
2016	112.183	77.181	164.518	0	0	0
2017	120.006	75.510	179.022	0	0	0
2018	127.694	74.560	194.158	0	0	0
2019	135.180	74.227	211.917	0	0	0
$F_{40\%}$						
2010	86.472	79.895	92.660	17.922	16.558	19.204
2011	75.212	69.491	80.594	17.677	16.332	18.942
2012	61.098	57.260	65.015	15.108	13.114	16.659
2013	50.784	47.747	54.144	10.276	9.049	11.594
2014	48.262	40.557	61.825	8.169	6.404	11.203
2015	52.063	35.486	84.332	8.134	4.688	12.654
2016	57.137	33.220	93.338	9.210	3.797	16.723
2017	61.517	34.420	100.608	10.485	3.712	18.852
2018	65.026	34.431	107.037	11.566	3.750	20.348
2019	67.945	35.320	114.369	12.422	3.851	21.790
$F_{35\%}$						
2010	82.932	76.624	88.866	21.483	19.849	23.020
2011	69.364	64.087	74.326	20.278	18.736	21.730
2012	55.646	52.255	58.764	15.244	13.207	17.227
2013	46.046	43.305	49.087	10.157	8.966	11.389
2014	44.121	36.656	57.380	8.125	6.286	11.307
2015	48.104	32.194	78.826	8.417	4.586	14.060
2016	53.007	30.429	86.608	9.775	3.774	18.694
2017	56.987	31.834	92.746	11.251	3.762	20.835
2018	59.981	31.737	97.679	12.449	3.900	22.278
2019	62.389	32.631	105.449	13.331	4.065	23.671

Table 9. List of years, survey stations, dates and red king crab sizes founded in groundfish stomachs during NMFS summer trawl surveys. All identified crabs are females, mostly mature females. (Source: G.M. Lang, NMFS, Seattle).

YEAR	RLAT	RLONG	STATION	DATE	PRED_LEN	RKC CL(mm)
1984	57.99	-160.87	J-12	6/13/1984	92	110
1984	57.33	-162.16	H-10	6/14/1984	79	130
1981	57.34	-162.13	H-10	5/29/1981	67	121
1981	57.34	-162.13	H-10	5/29/1981	67	106
1981	56.69	-161.00	F-12	6/1/1981	66	100
1981	56.69	-161.00	F-12	6/1/1981	69	53
1981	57.01	-160.95	G-12	6/1/1981	69	160
1981	57.99	-160.87	J-12	6/21/1981	51	91
1981	57.99	-160.87	J-12	6/21/1981	62	95
1985	56.95	-159.85	G-14	10/29/1985	85	52
1986	57.67	-161.49	I-11	6/7/1986	89	91
1989	56.17	-161.52	D-11	6/4/1989	95	84
1989	56.17	-161.52	D-11	6/4/1989	95	99
1991	57.00	-159.12	G-15	6/8/1991	56	17
1992	57.32	-162.15	H-10	6/9/1992	98	101
1992	57.32	-162.15	H-10	6/9/1992	98	87
1992	57.32	-162.15	H-10	6/9/1992	98	95
1992	57.32	-162.15	H-10	6/9/1992	97	117
1992	56.67	-160.99	F-12	6/7/1992	89	144
1985	56.42	-161.58	E-11	4/25/1985	82	94
1992	56.67	-160.99	F-12	6/7/1992	89	144
1992	57.32	-162.15	H-10	6/9/1992	98	101
1992	57.32	-162.15	H-10	6/9/1992	98	87
1992	57.32	-162.15	H-10	6/9/1992	98	95
1992	57.32	-162.15	H-10	6/9/1992	97	117
2000	56.00	-162.25	D-10	5/28/2000	75	120
2002	57.68	-160.27	I-13	6/3/2002	70	125

Table 10. Summary of red king crab biomass (million lbs) in Bristol Bay that were consumed by groundfish during late May to September. Pacific cod is the main predator. (Source: G.M. Lang, NMFS, Seattle).

Year	Red king crab biomass
1984	3.719
1985	0.000
1986	14.457
1987	7.403
1988	0.000
1989	0.203
1990	1.853
1991	0.039
1992	4.488
1993	3.833
1994	1.545
1995	0.993
1996	0.000
1997	0.000
1998	2.192
1999	1.718
2000	1.199
2001	0.000
2002	2.008
2003	0.000
2004	0.000
2005	11.677

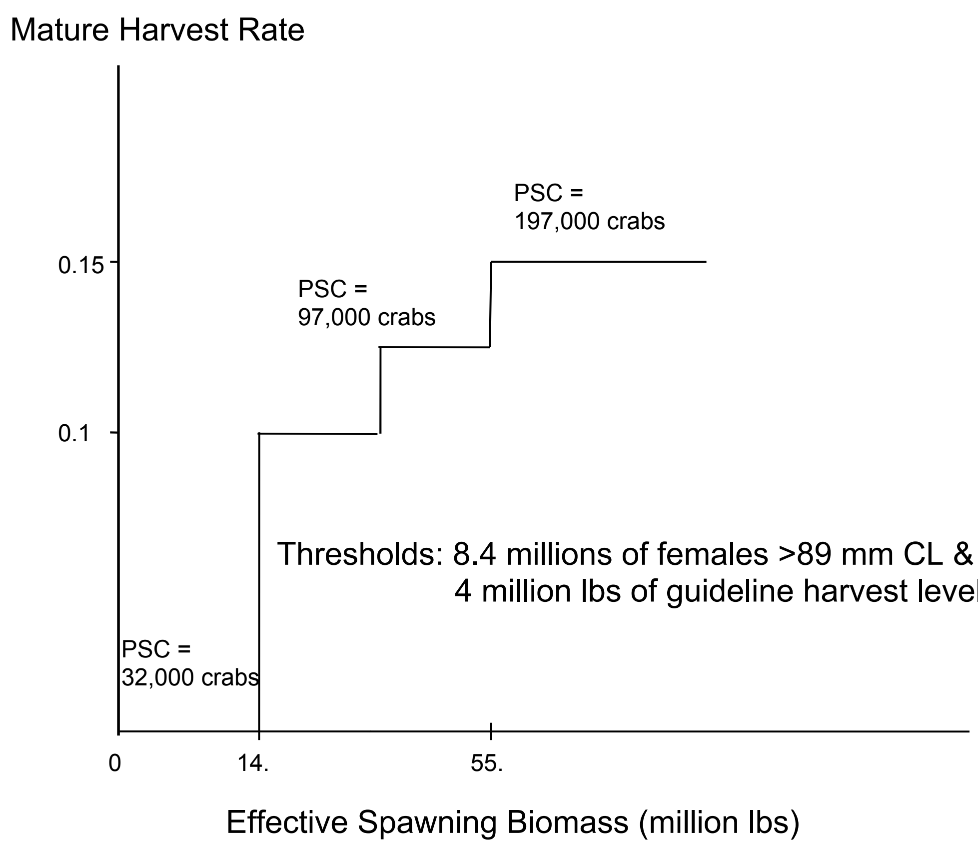


Figure 1. Current harvest rate strategy (line) for the Bristol Bay red king crab fishery and annual prohibited species catch (PSC) limits (numbers of crabs) of Bristol Bay red king crabs in the groundfish fisheries in zone 1 in the eastern Bering Sea. Harvest rates are based on current-year estimates of effective spawning biomass (ESB), whereas PSC limits apply to previous-year ESB.

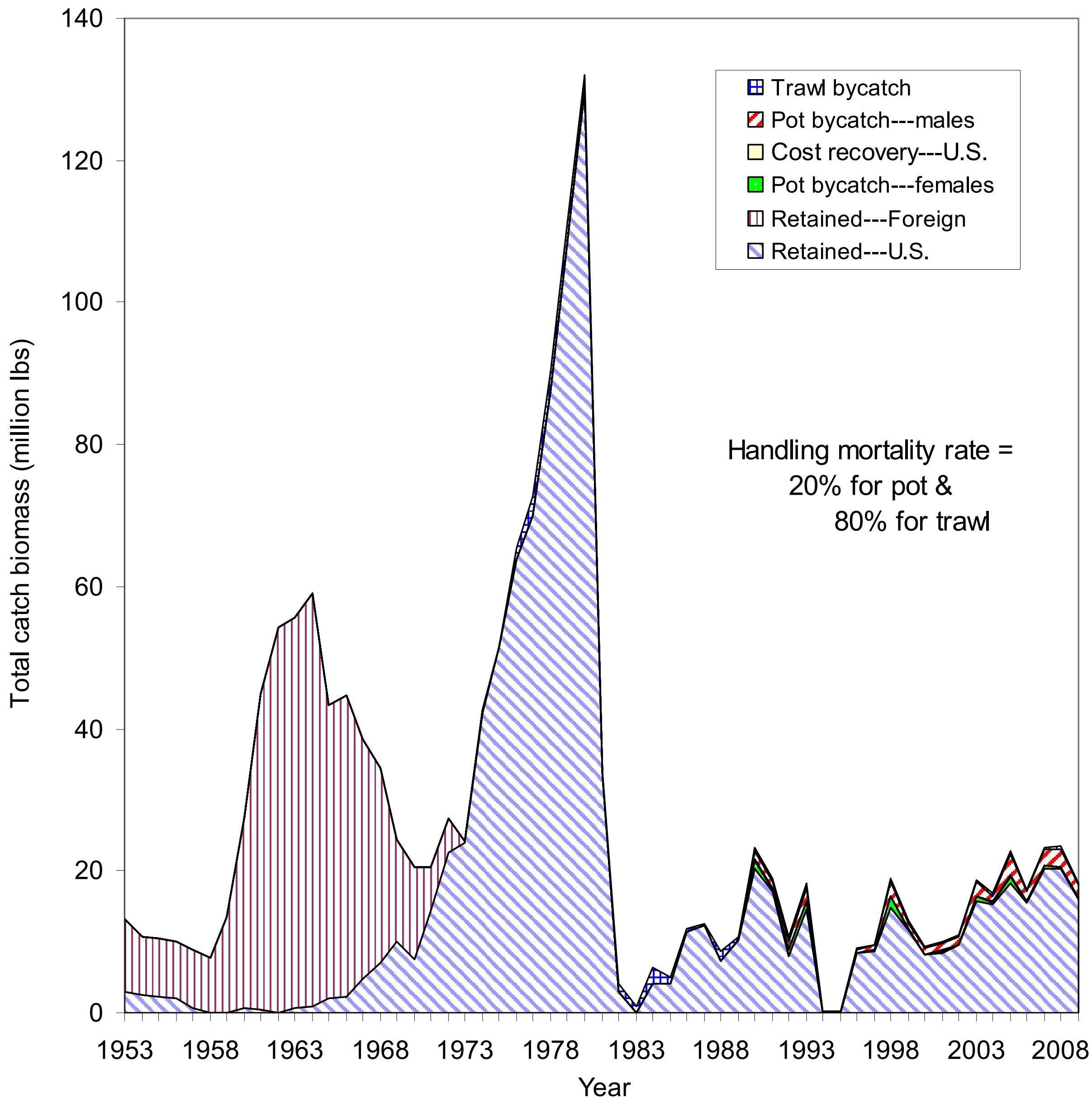


Figure 2. Retained catch biomass and bycatch mortality biomass (million lbs) for Bristol Bay red king crab from 1960 to 2009. Handling mortality rates were assumed to be 0.2 for the directed pot fishery and 0.8 for the trawl fisheries.

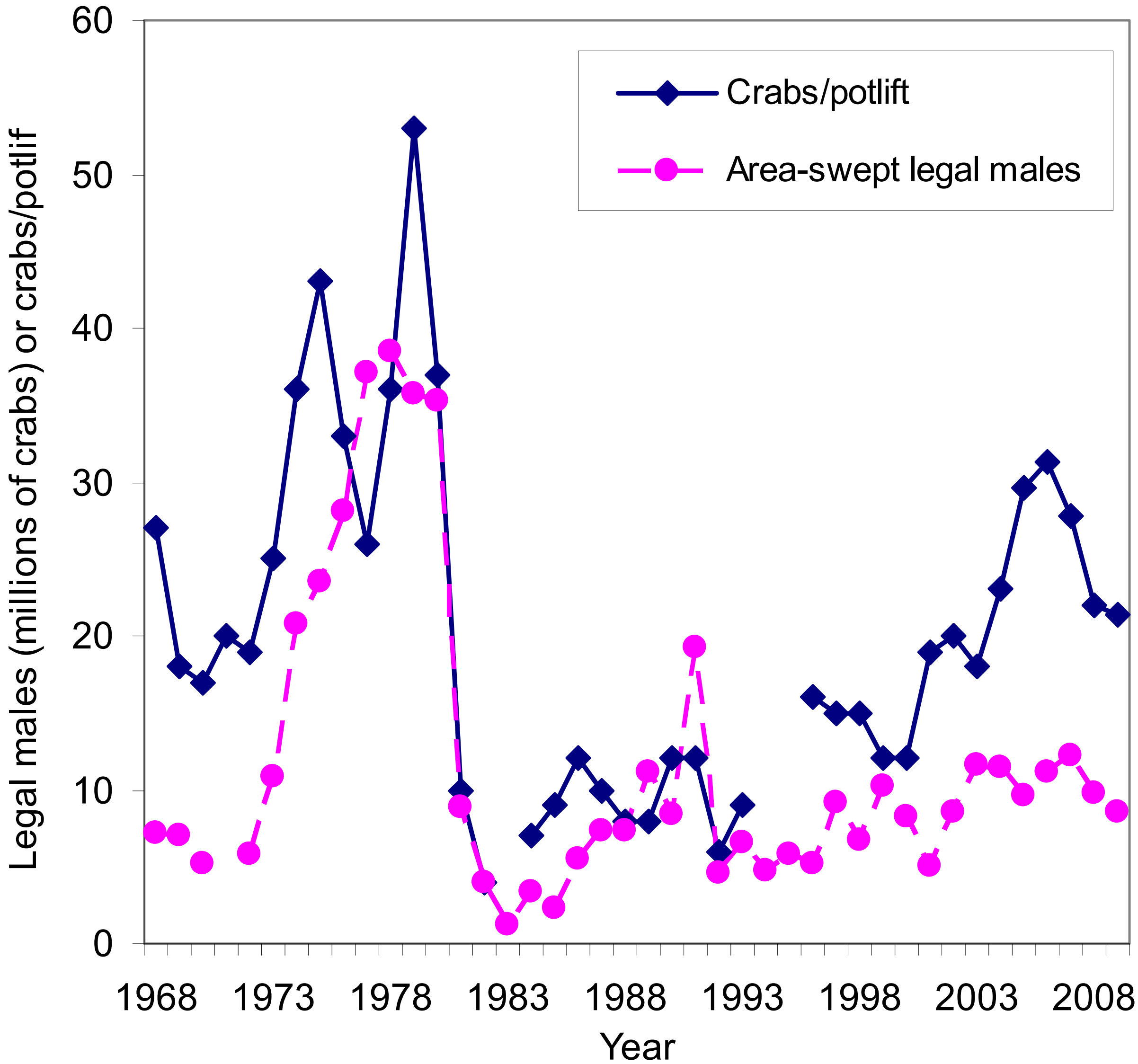


Figure 3. Comparison of survey legal male abundances and catches per unit effort for Bristol Bay red king crab from 1968 to 2009.

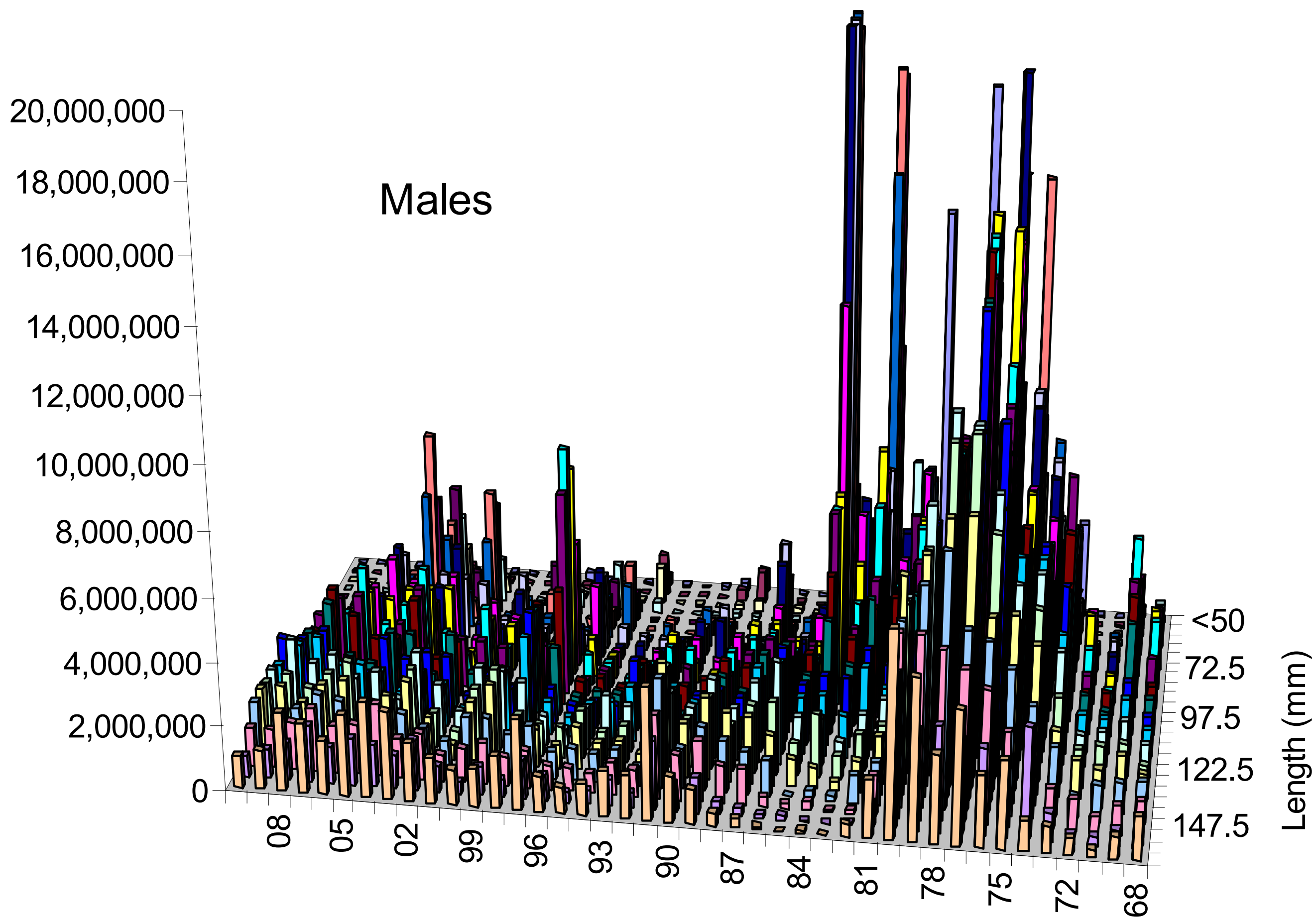


Figure 4. Survey abundances by length for male Bristol Bay red king crabs from 1968 to 2010.

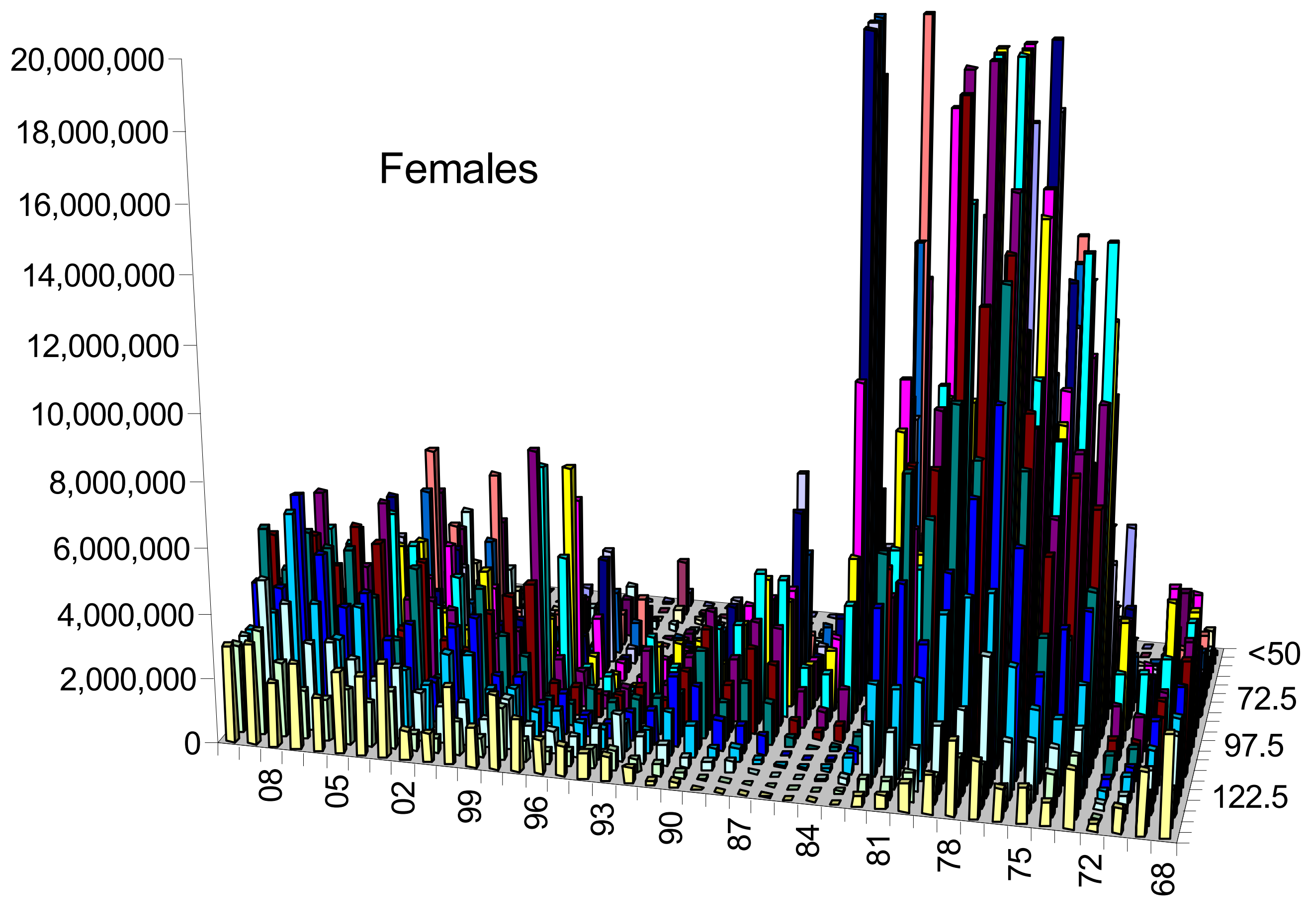


Figure 5. Survey abundances by length for female Bristol Bay red king crabs from 1968 to 2010.

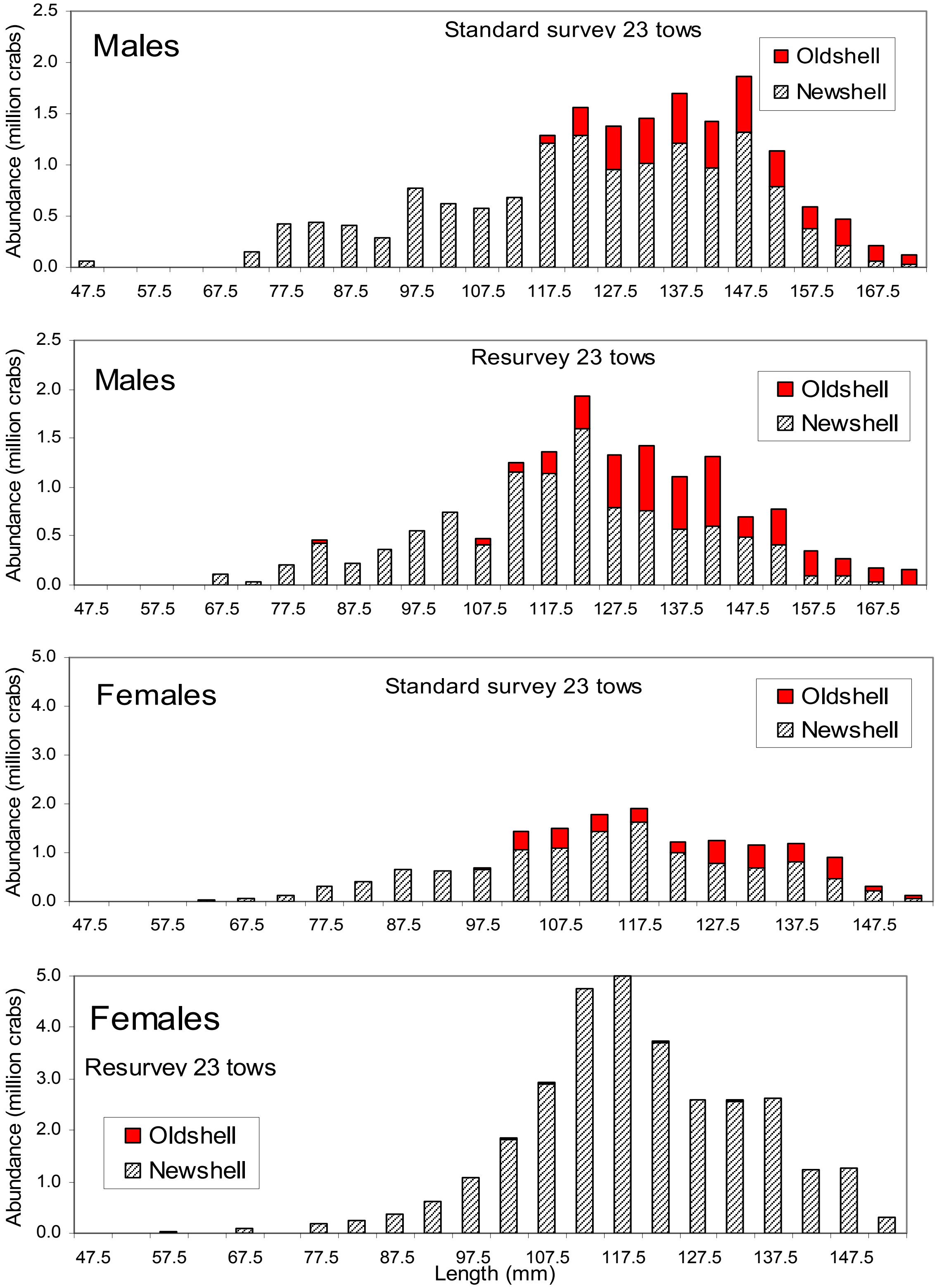


Figure 6. Comparison of area-swept estimates of abundance in 23 stations from the standard trawl survey and resurvey in 2010.

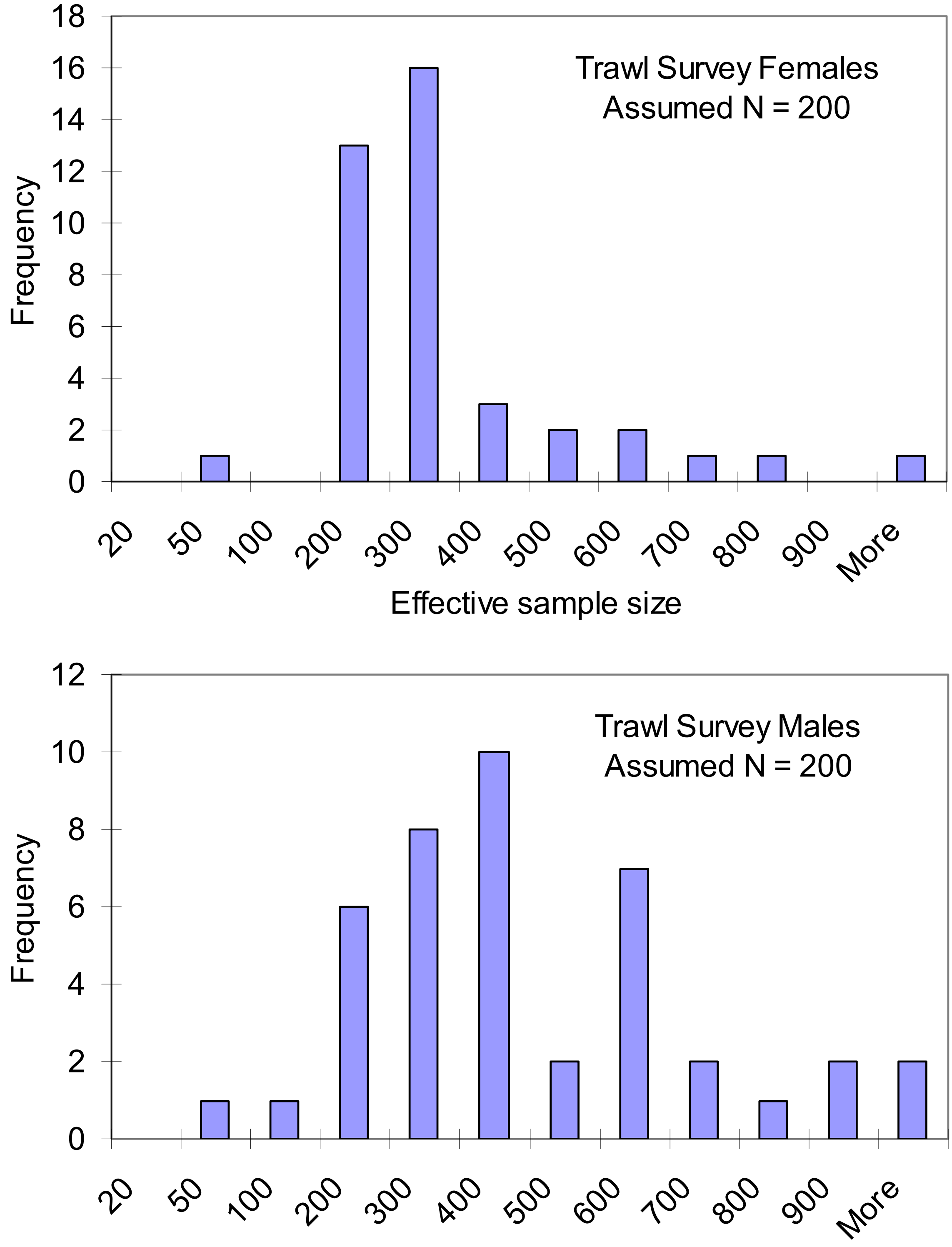
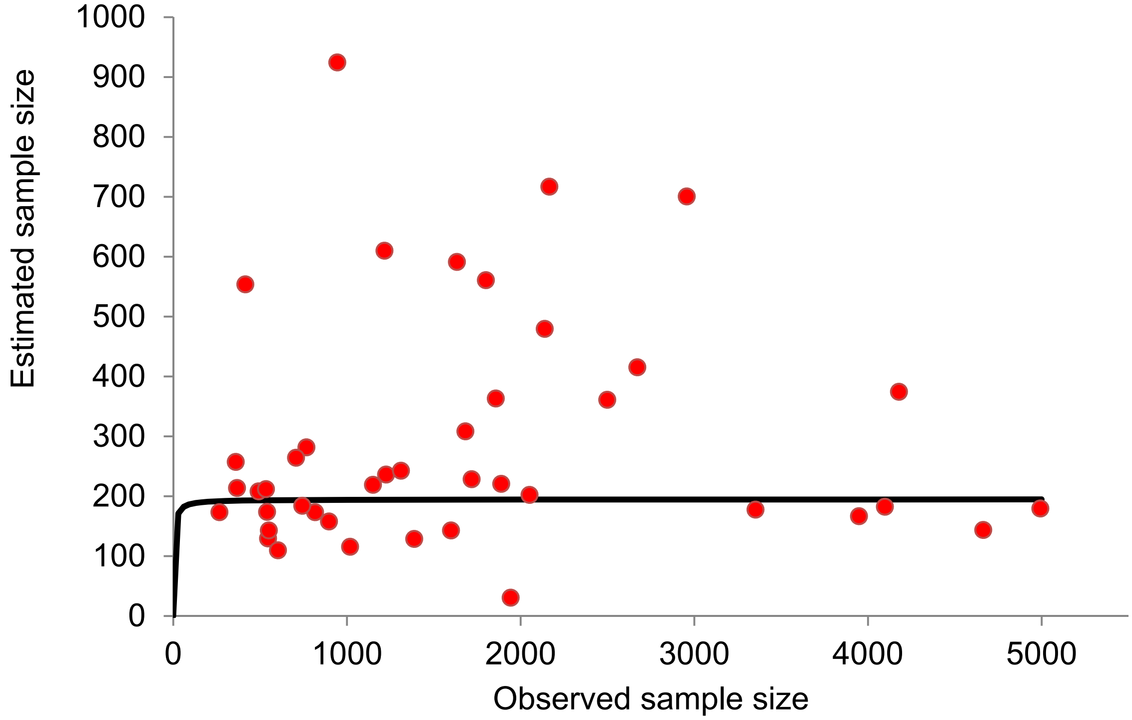


Figure 7a(0). Estimated effective sample sizes for length/sex composition data with scenario 0: trawl survey data.



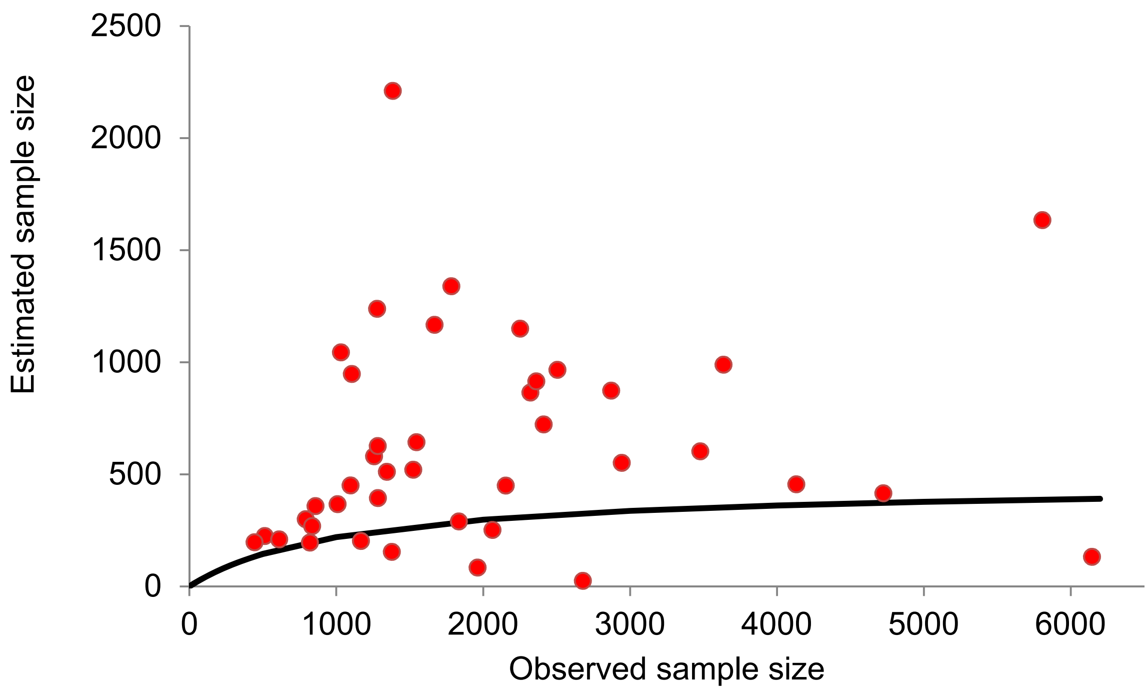
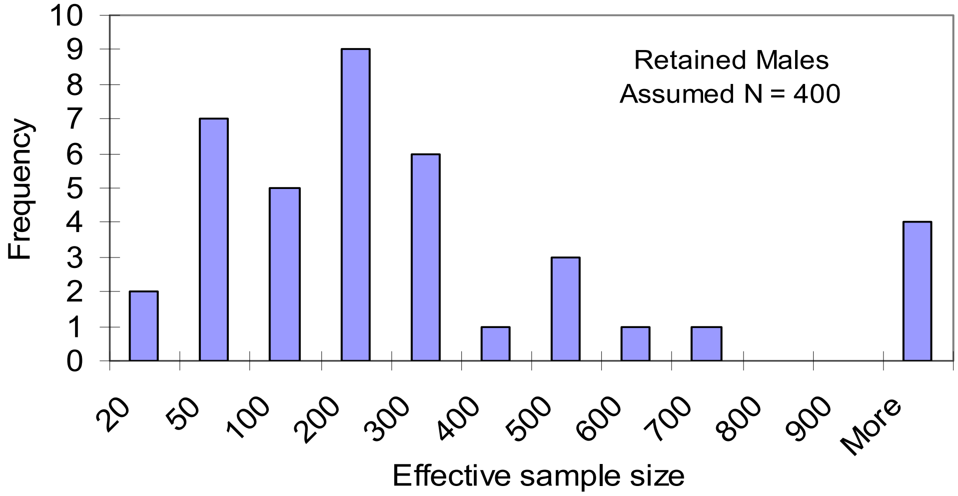
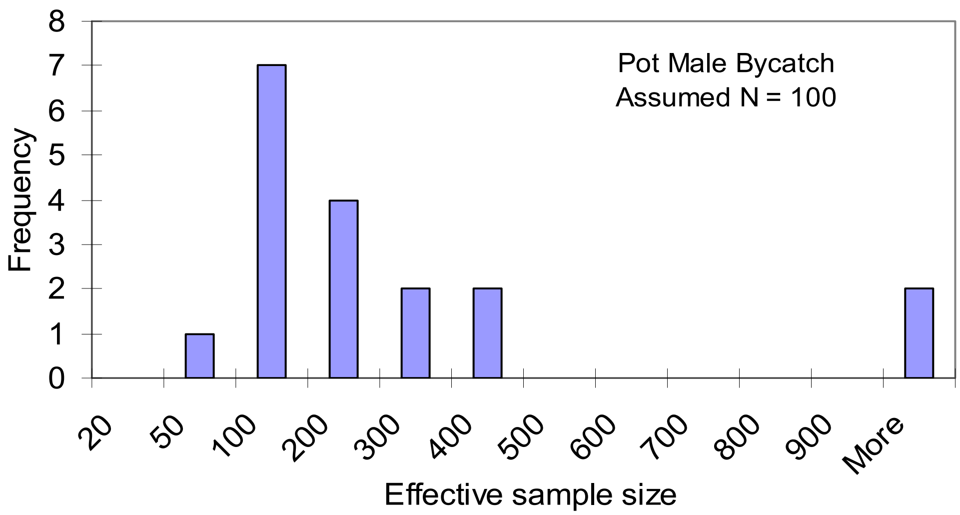


Figure 7a(7). Relationship between observed and estimated effective sample sizes for length/sex composition data with scenario 7: trawl survey data.





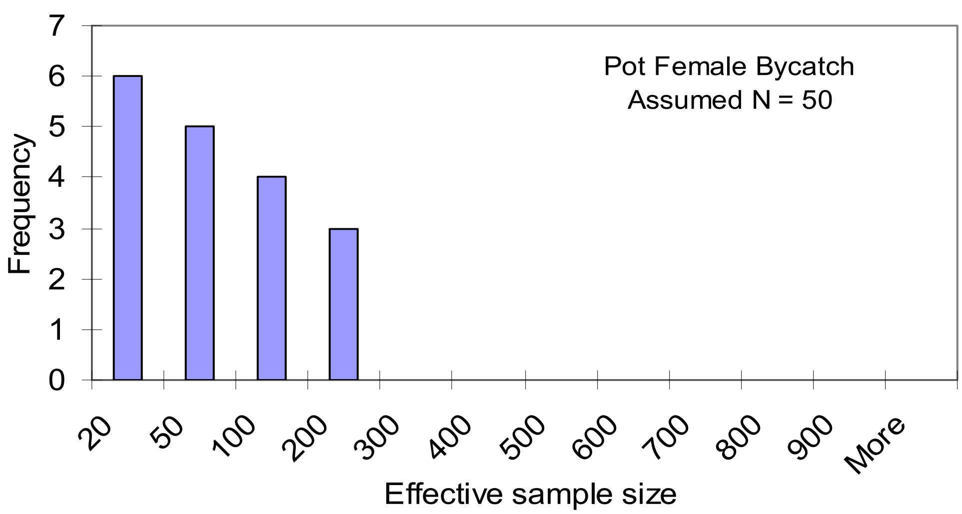


Figure 7b(0). Estimated effective sample sizes for length/sex composition data with scenario 0: directed pot fishery data.

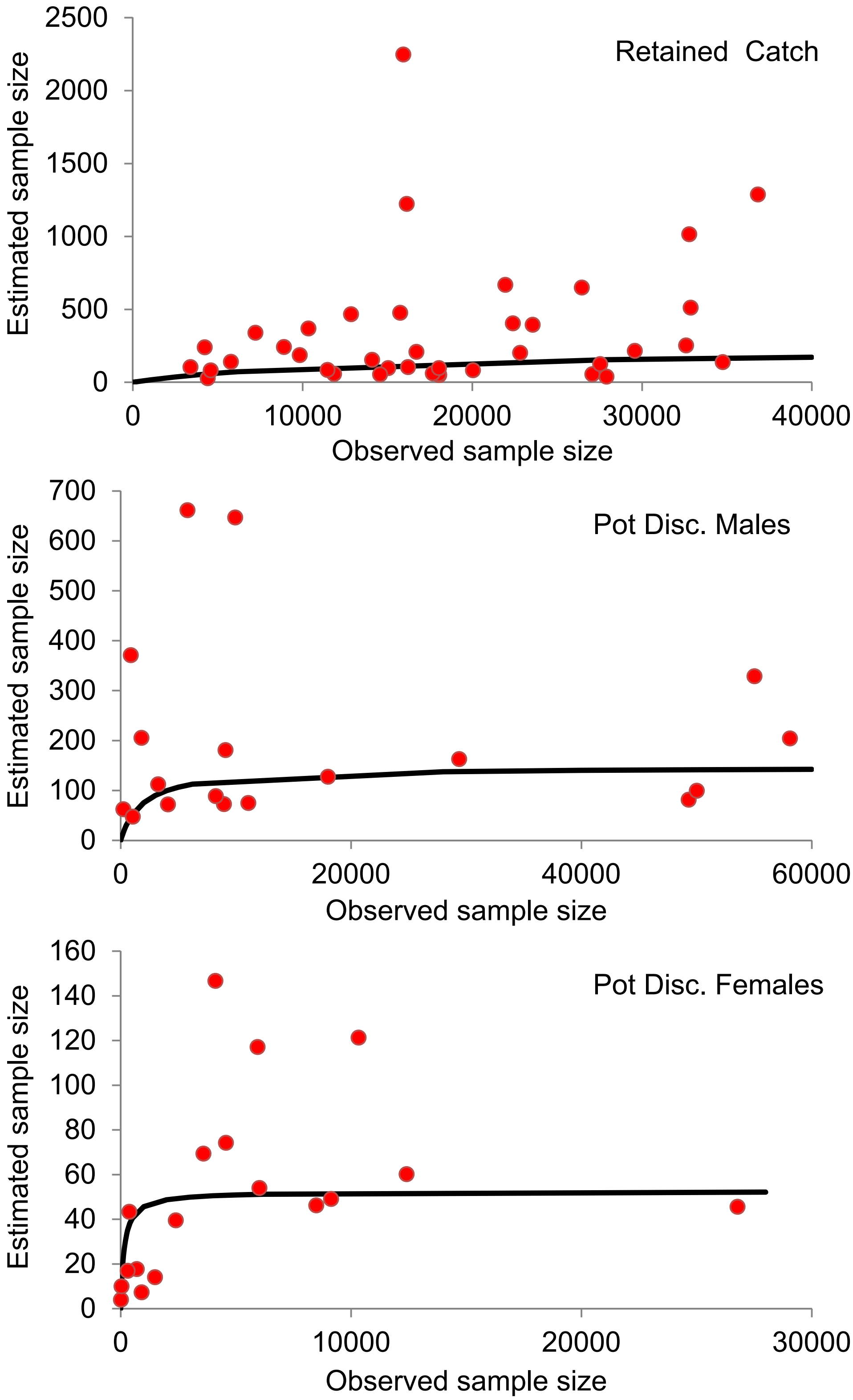


Figure 7b(7). Relationship between observed and estimated effective sample sizes for length/sex composition data with scenario 7: directed pot fishery data.

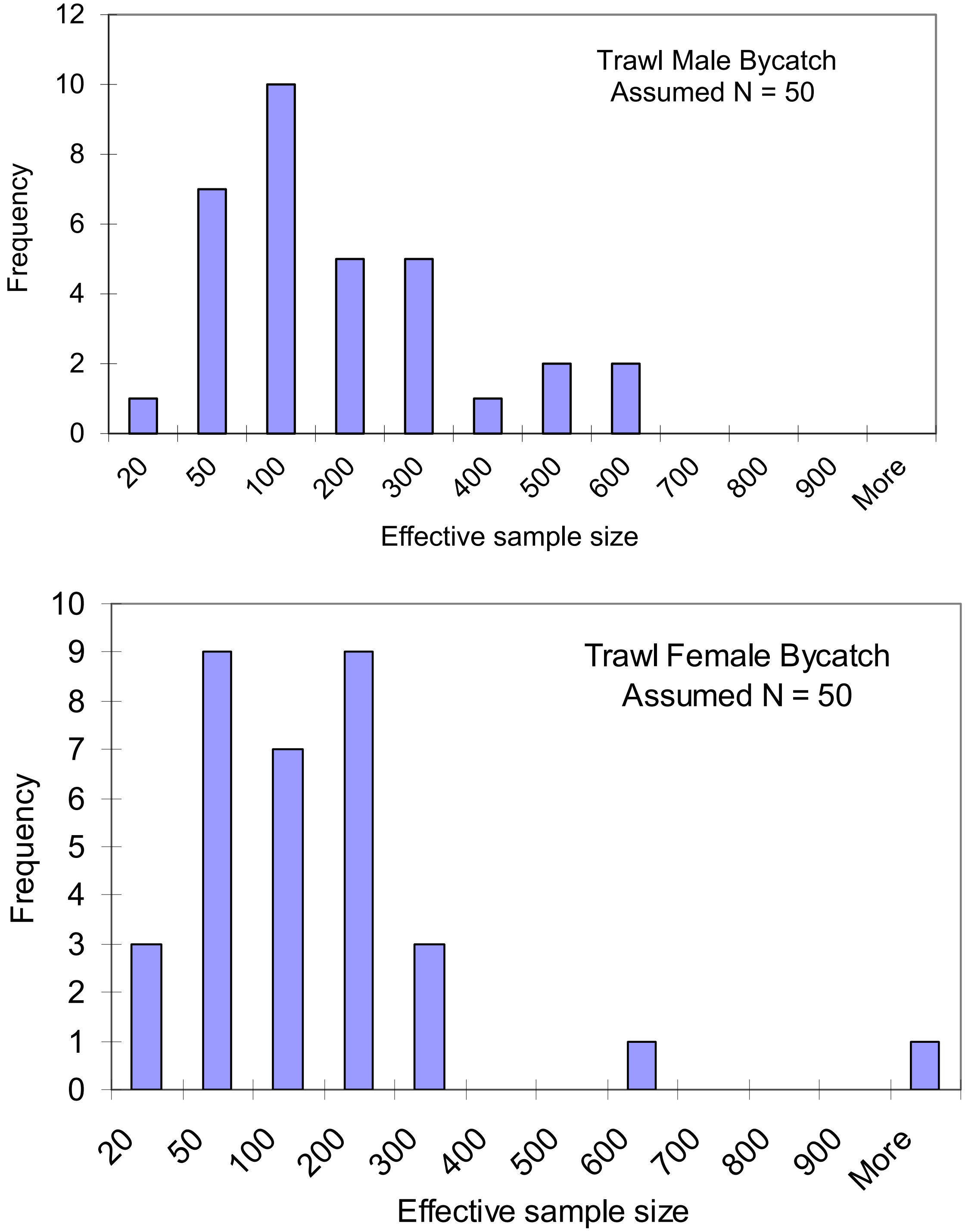


Figure 7c(0). Estimated effective sample sizes for length/sex composition data with scenario 0: trawl bycatch data.

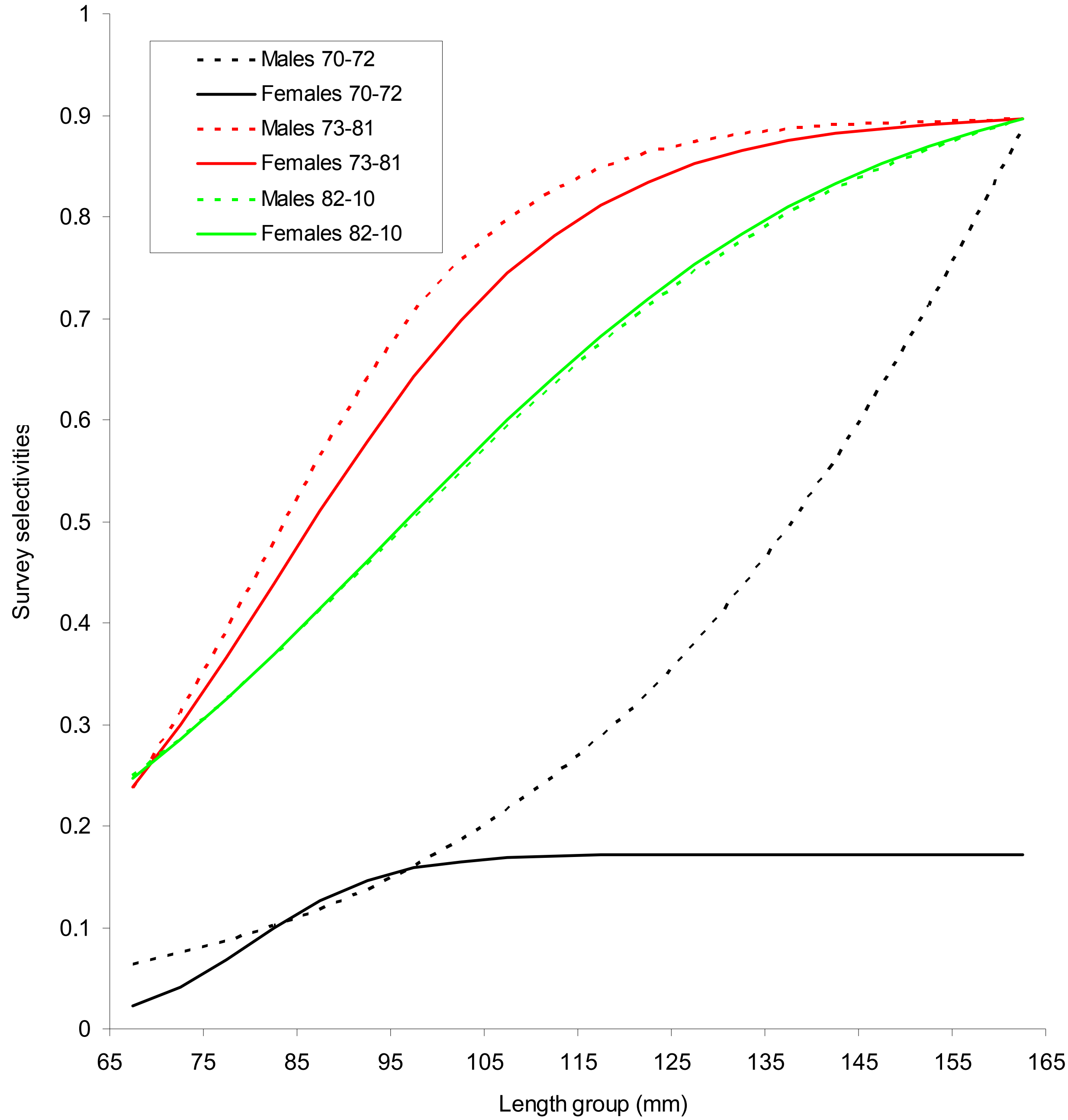
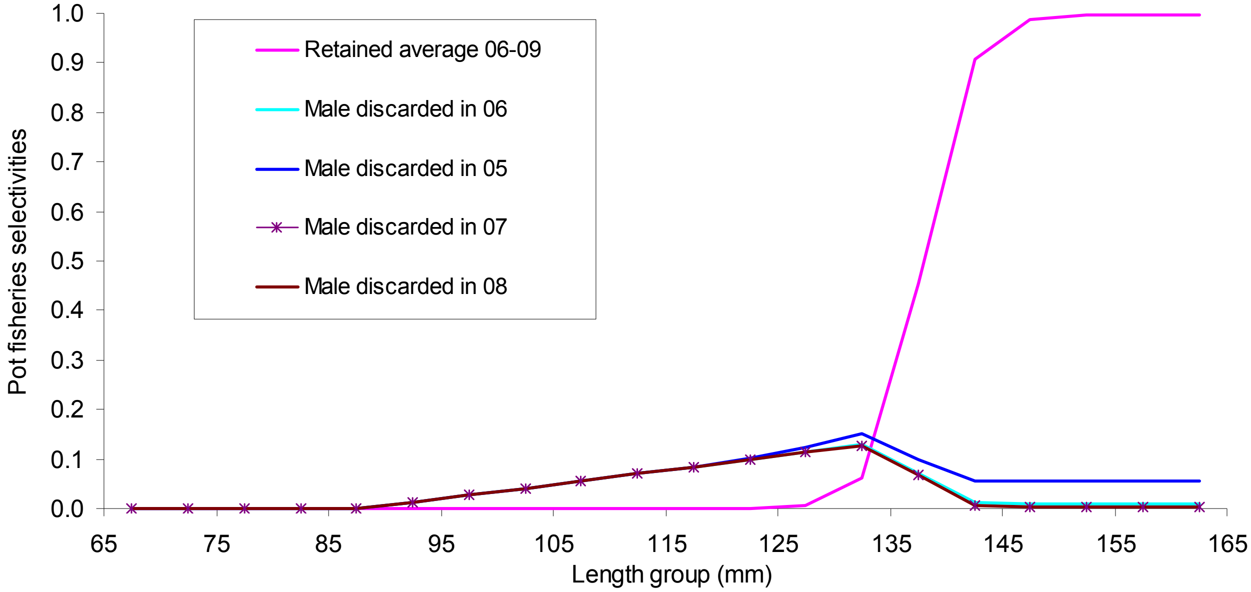


Figure 8a(0). Estimated trawl survey selectivities under scenario 0. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.



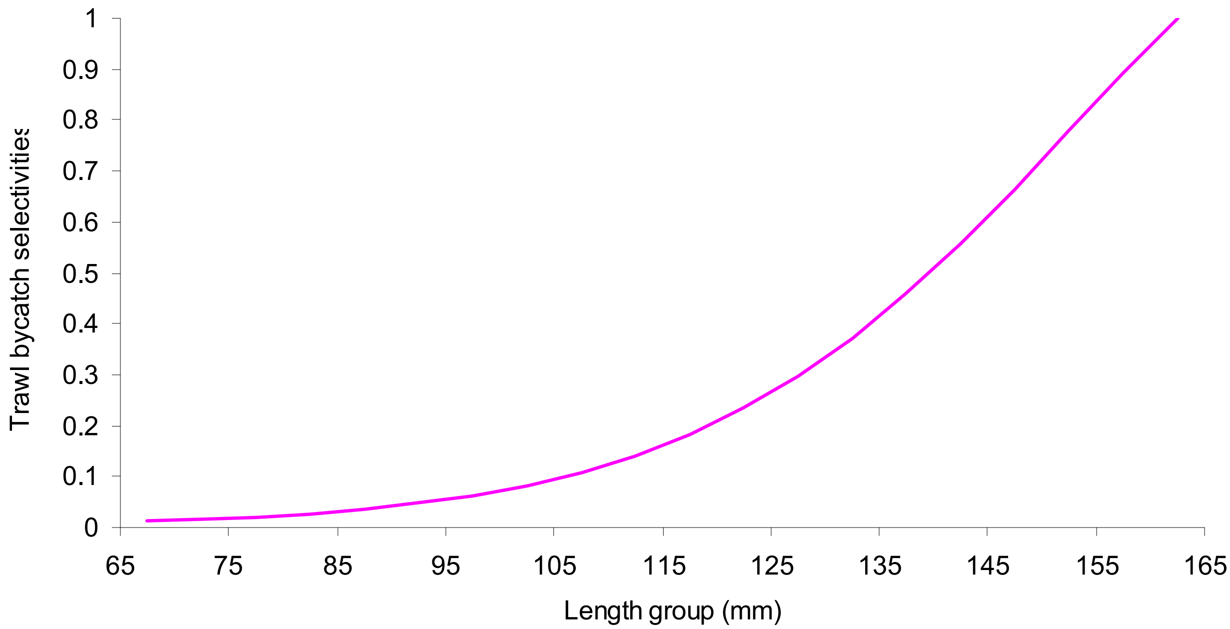


Figure 8b(0). Estimated pot fishery selectivities and groundfish trawl bycatch selectivities under scenario 0. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

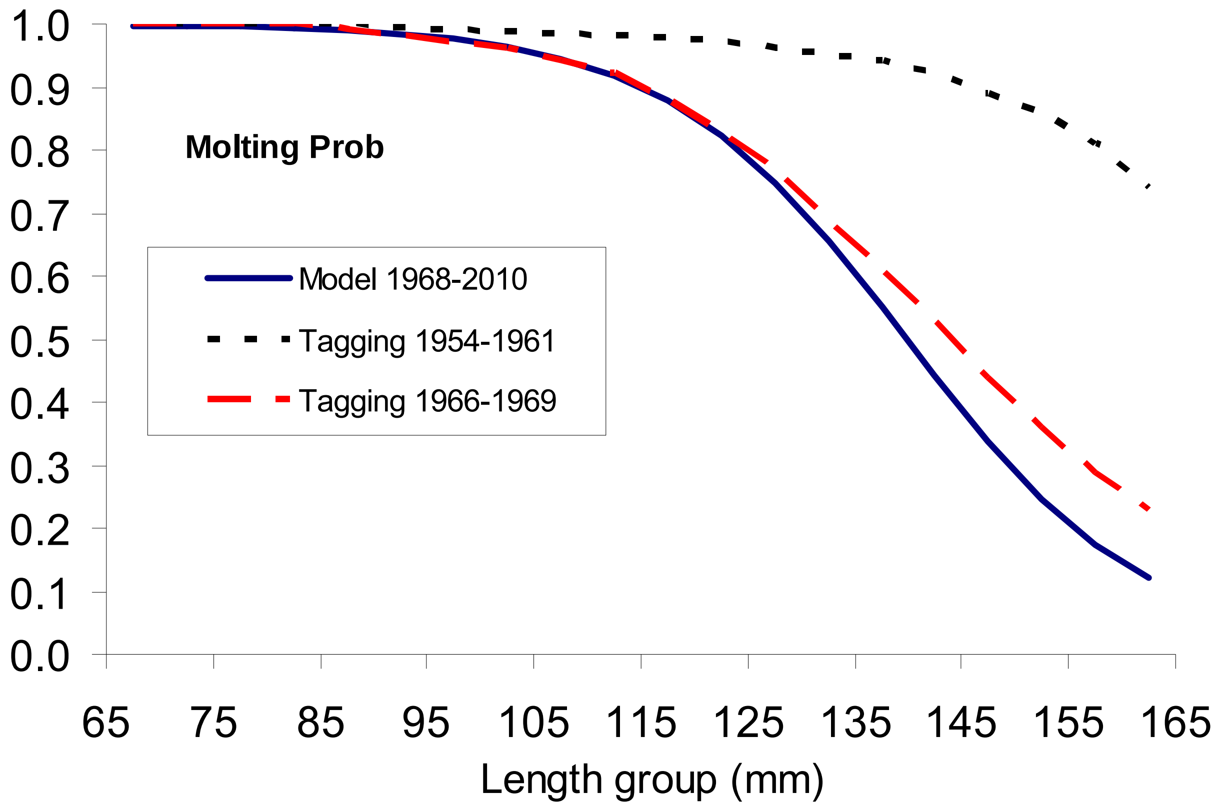


Figure 9(0). Comparison of estimated probabilities of molting of male red king crabs in Bristol Bay for different periods. Molting probabilities for periods 1954-1961 and 1966-1969 were estimated by Balsiger (1974) from tagging data. Molting probabilities for 1968-2010 were estimated with a length-based model with pot handling mortality rate to be 0.2 under scenario 0.

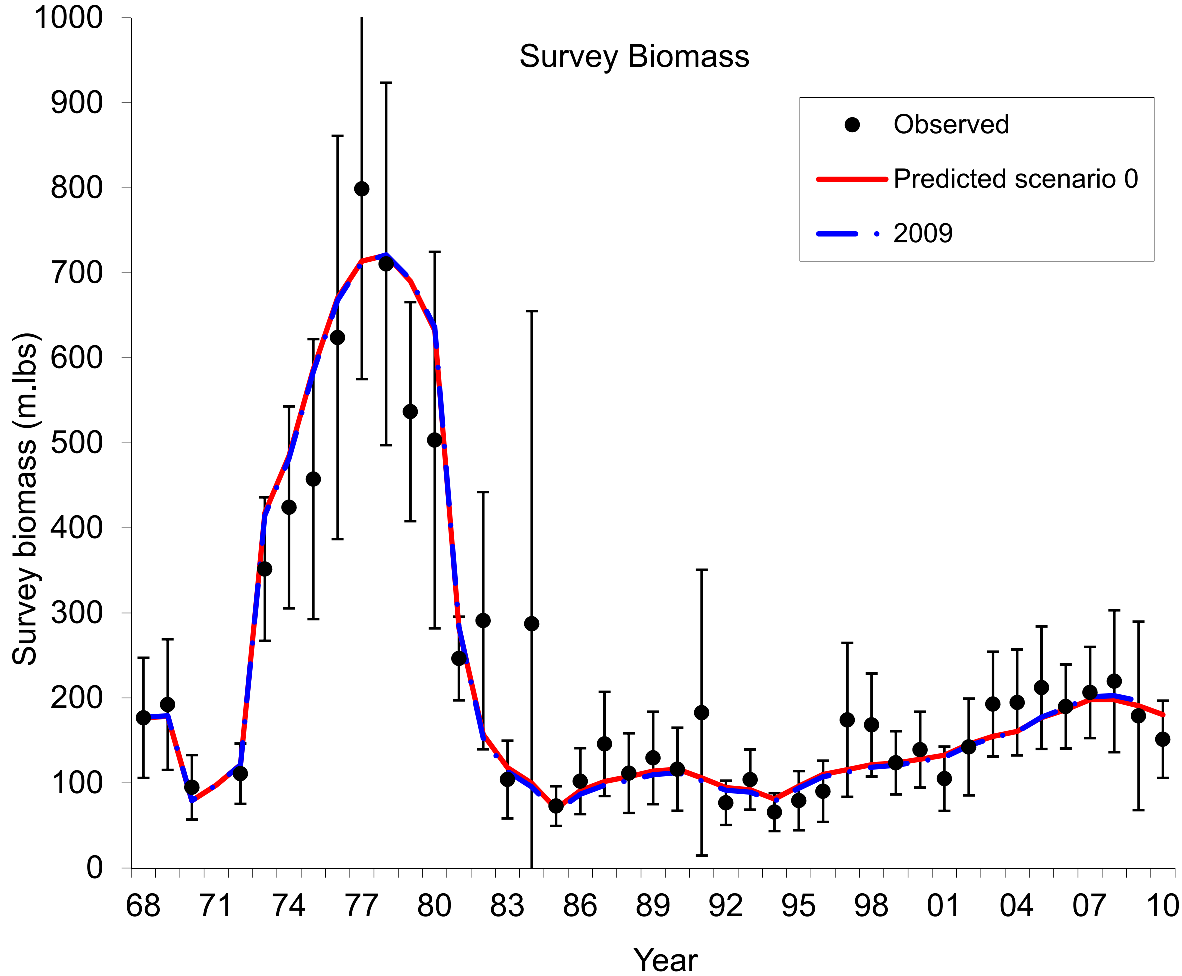


Figure 10a(0). Comparisons of area-swept estimates of total survey biomass and model prediction for scenario 0. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. The error bars are plus and minus 2 standard deviations.

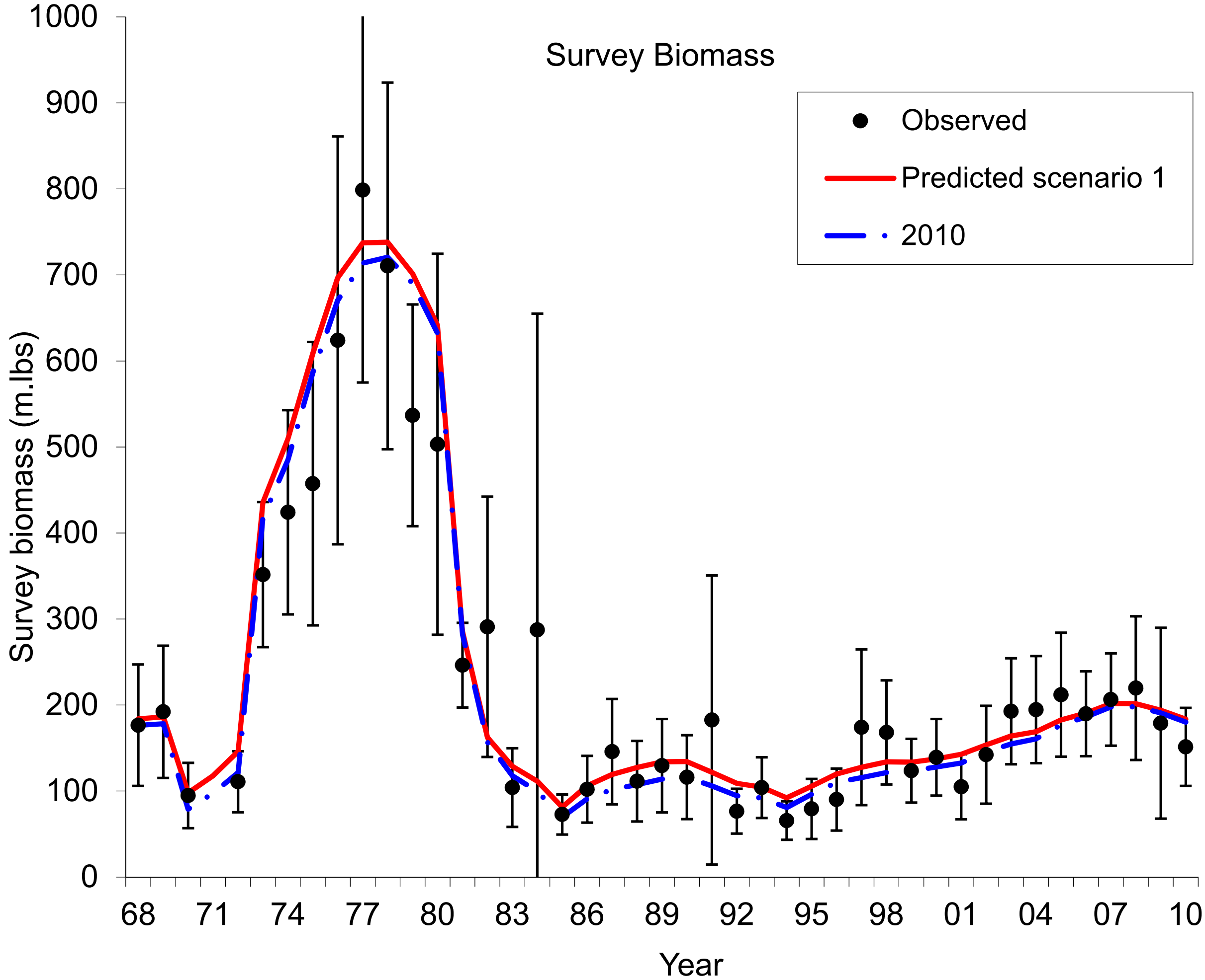


Figure 10a(1). Comparisons of area-swept estimates of total survey biomass and model prediction for scenario 1. Scenario 0 is labeled as "2010". Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. The error bars are plus and minus 2 standard deviations.

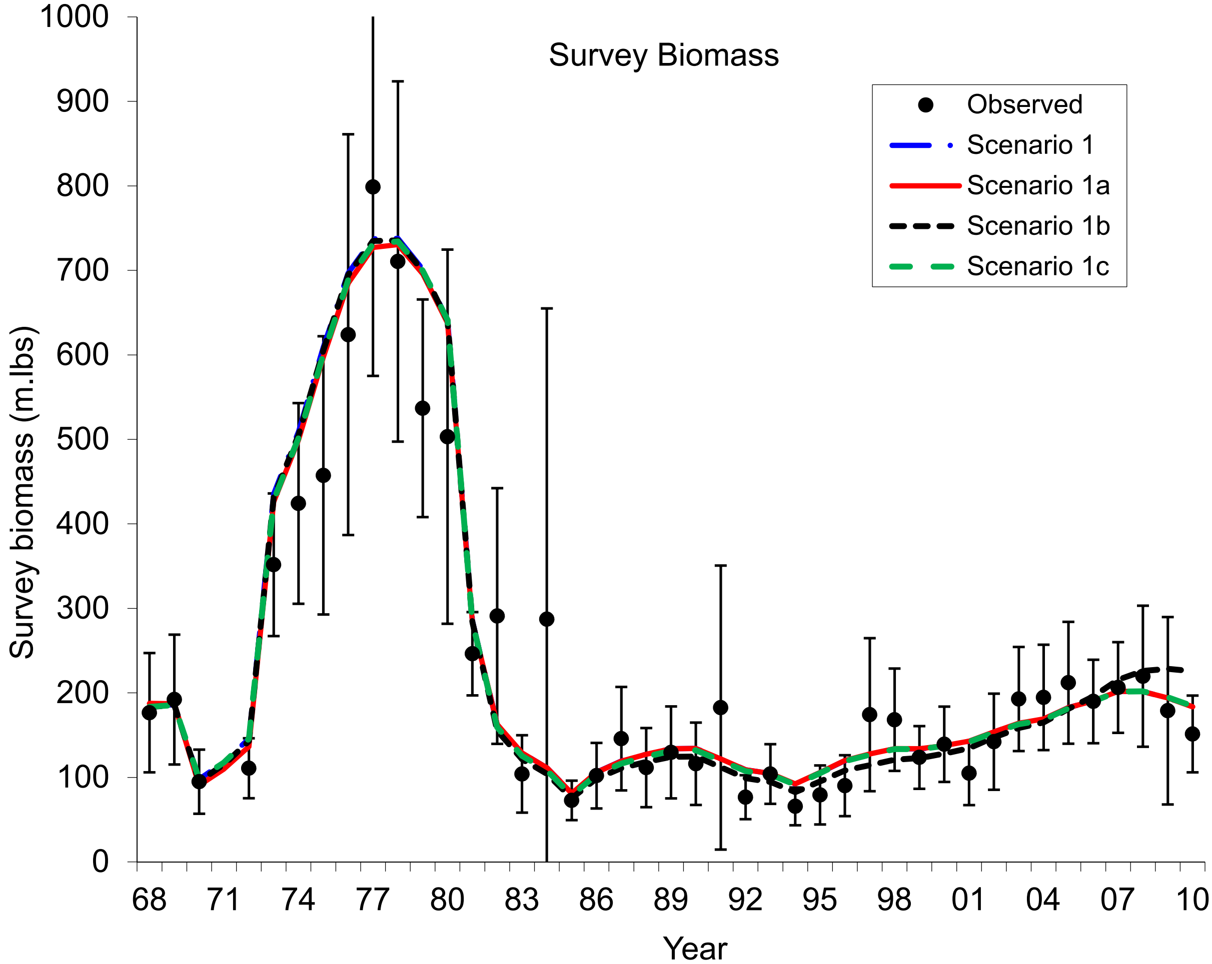


Figure 10a(1abc). Comparisons of area-swept estimates of total survey biomass and model prediction for scenarios 1, 1a, 1b and 1c. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. The error bars are plus and minus 2 standard deviations.

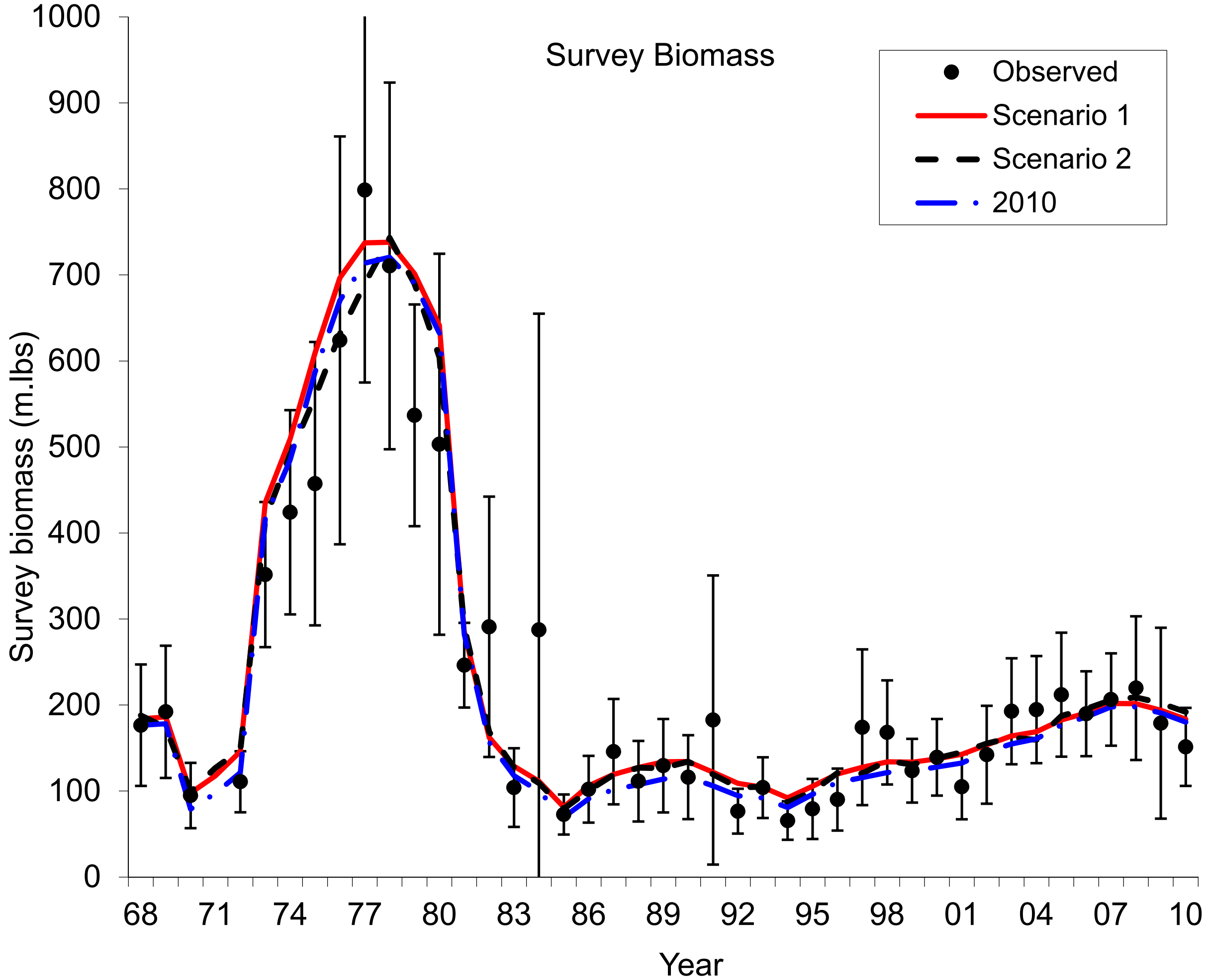


Figure 10a(2). Comparisons of area-swept estimates of total survey biomass and model prediction for scenarios 1&2. Scenario 0 is labeled as "2010". Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. The error bars are plus and minus 2 standard deviations.

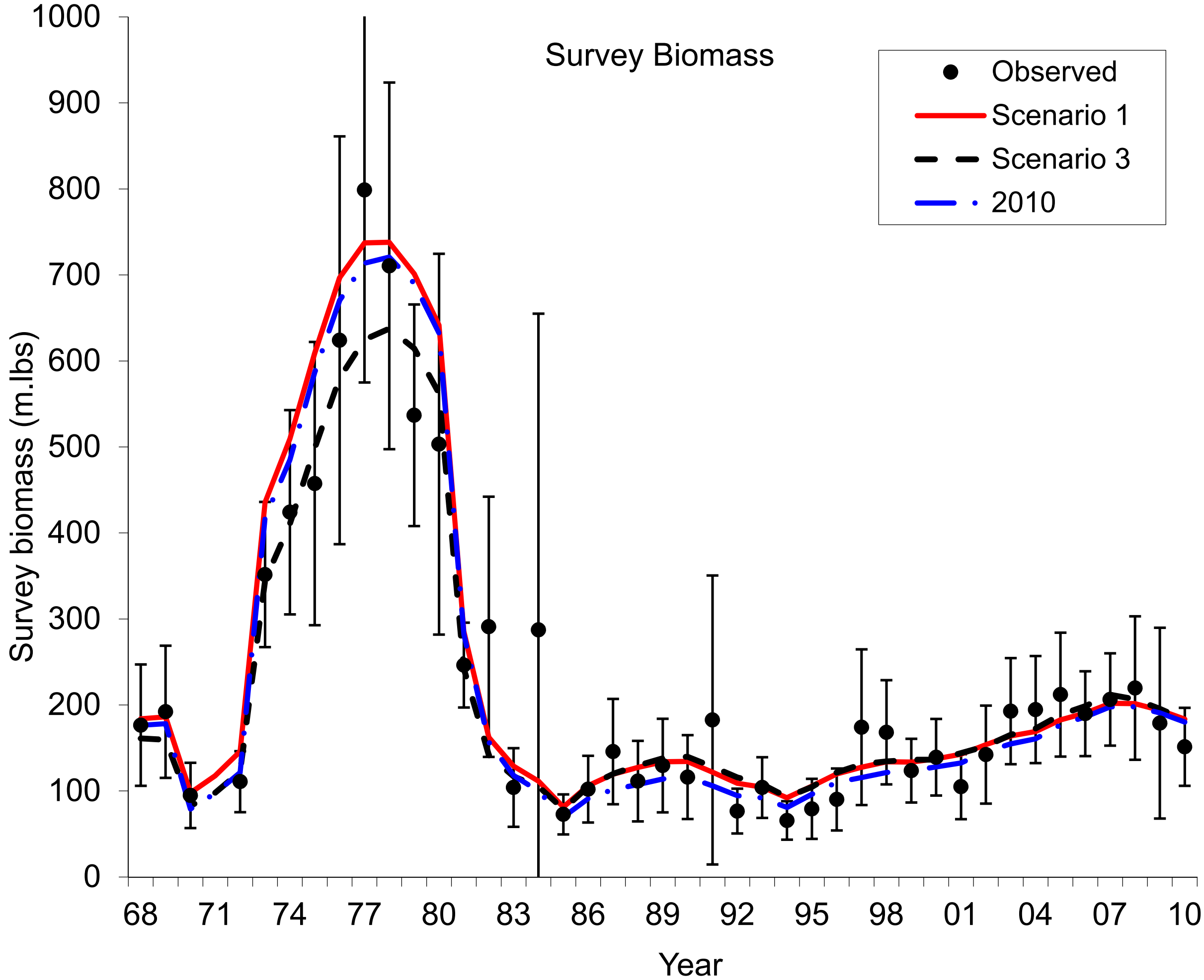


Figure 10a(3). Comparisons of area-swept estimates of total survey biomass and model prediction for scenario 3. Scenario 0 is labeled as “2010”. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. The error bars are plus and minus 2 standard deviations.

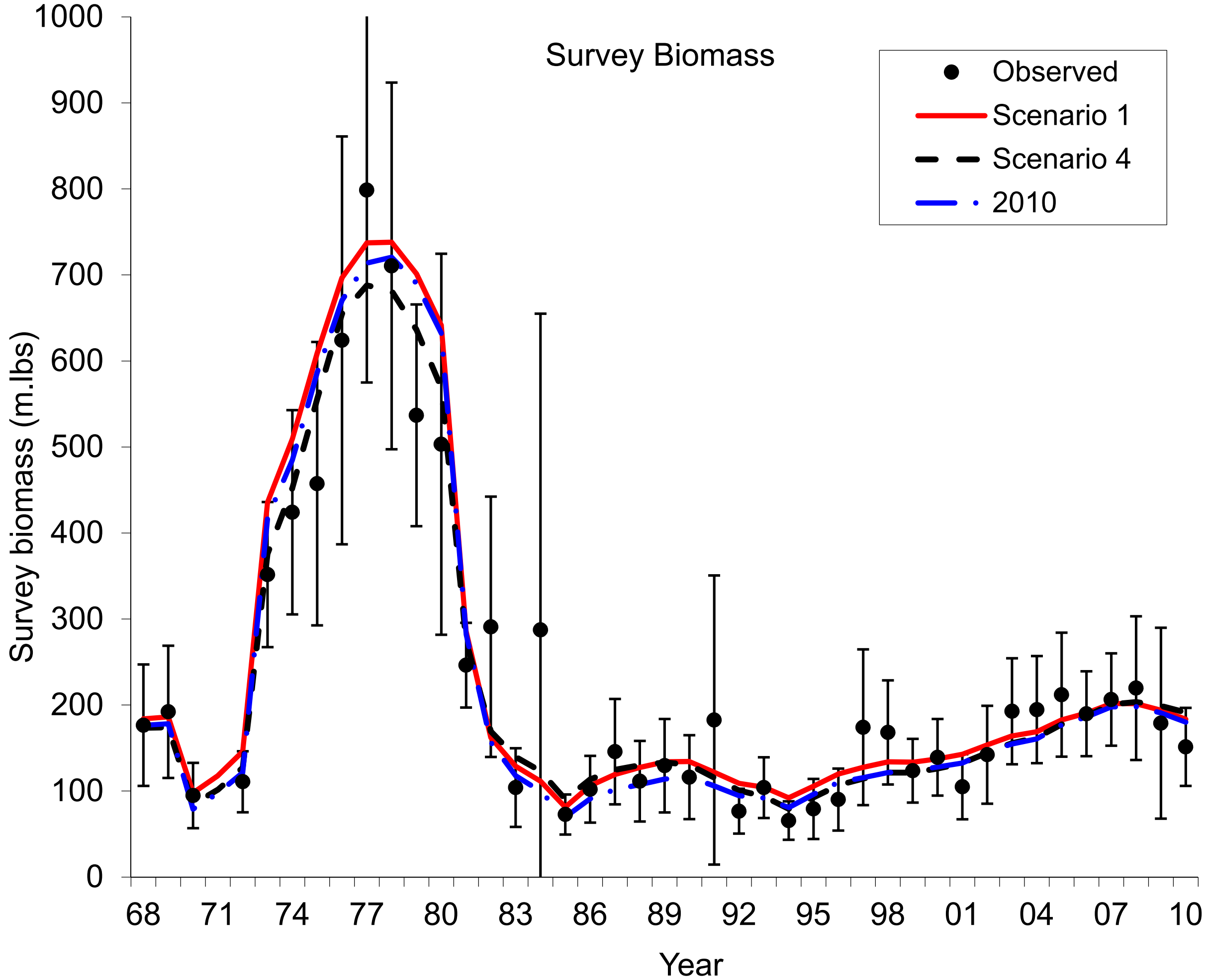


Figure 10a(4). Comparisons of area-swept estimates of total survey biomass and model prediction for scenarios 1 & 4. Scenario 0 is labeled as “2010”. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. The error bars are plus and minus 2 standard deviations.

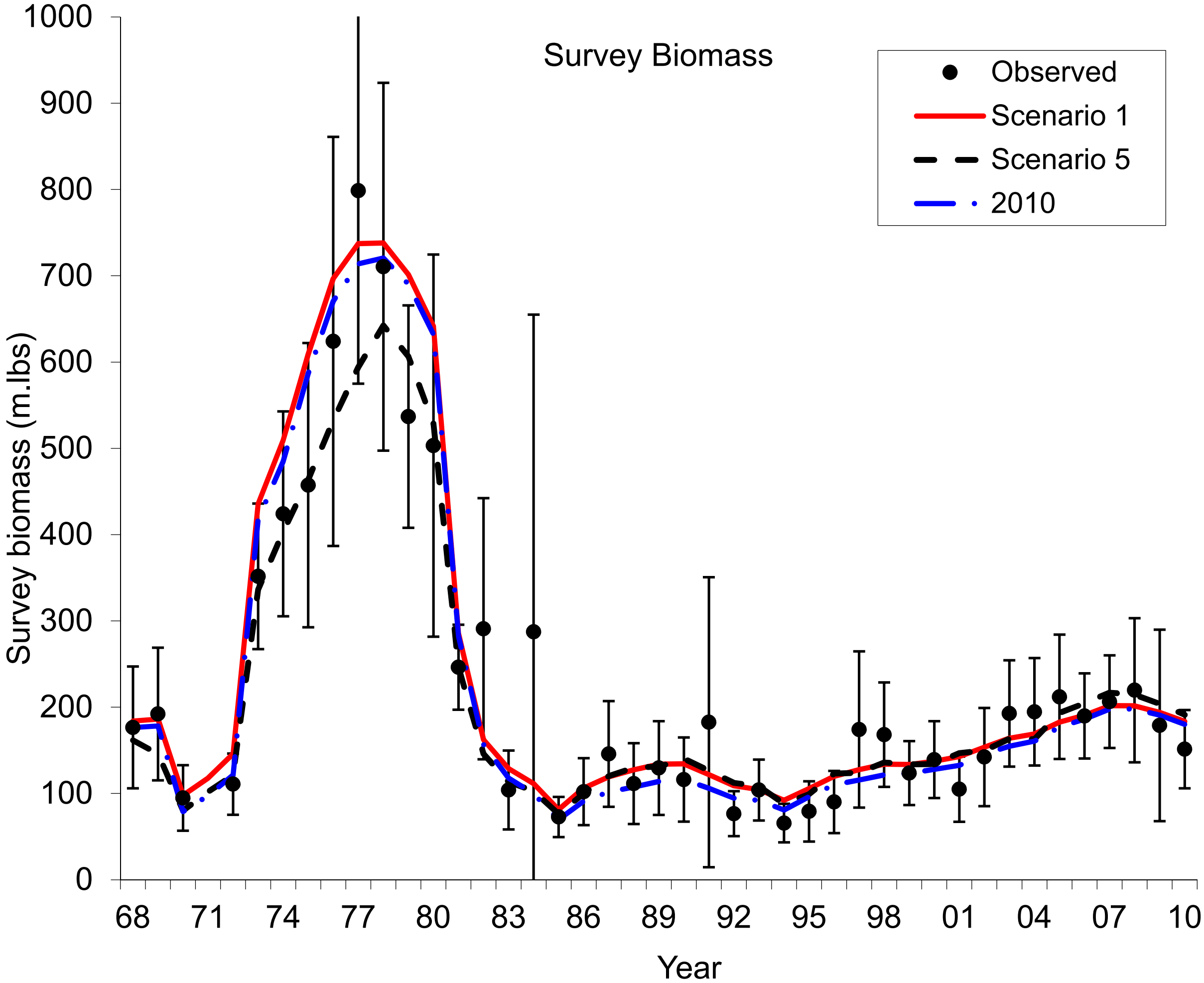


Figure 10a(5). Comparisons of area-swept estimates of total survey biomass and model prediction for scenarios 1 & 5. Scenario 0 is labeled as "2010". Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. The error bars are plus and minus 2 standard deviations.

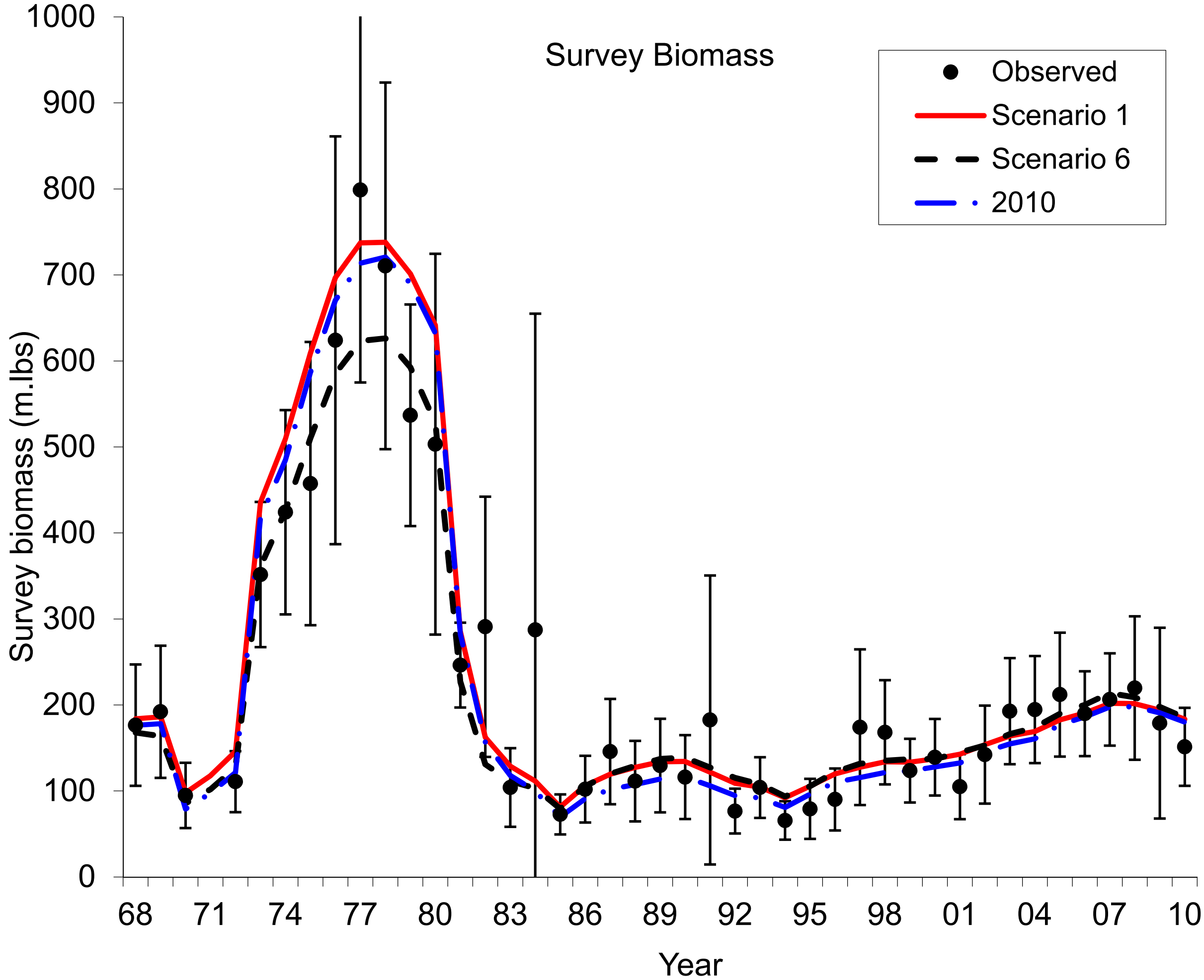


Figure 10a(6). Comparisons of area-swept estimates of total survey biomass and model prediction for scenarios 1 & 6. Scenario 0 is labeled as "2010". Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. The error bars are plus and minus 2 standard deviations.

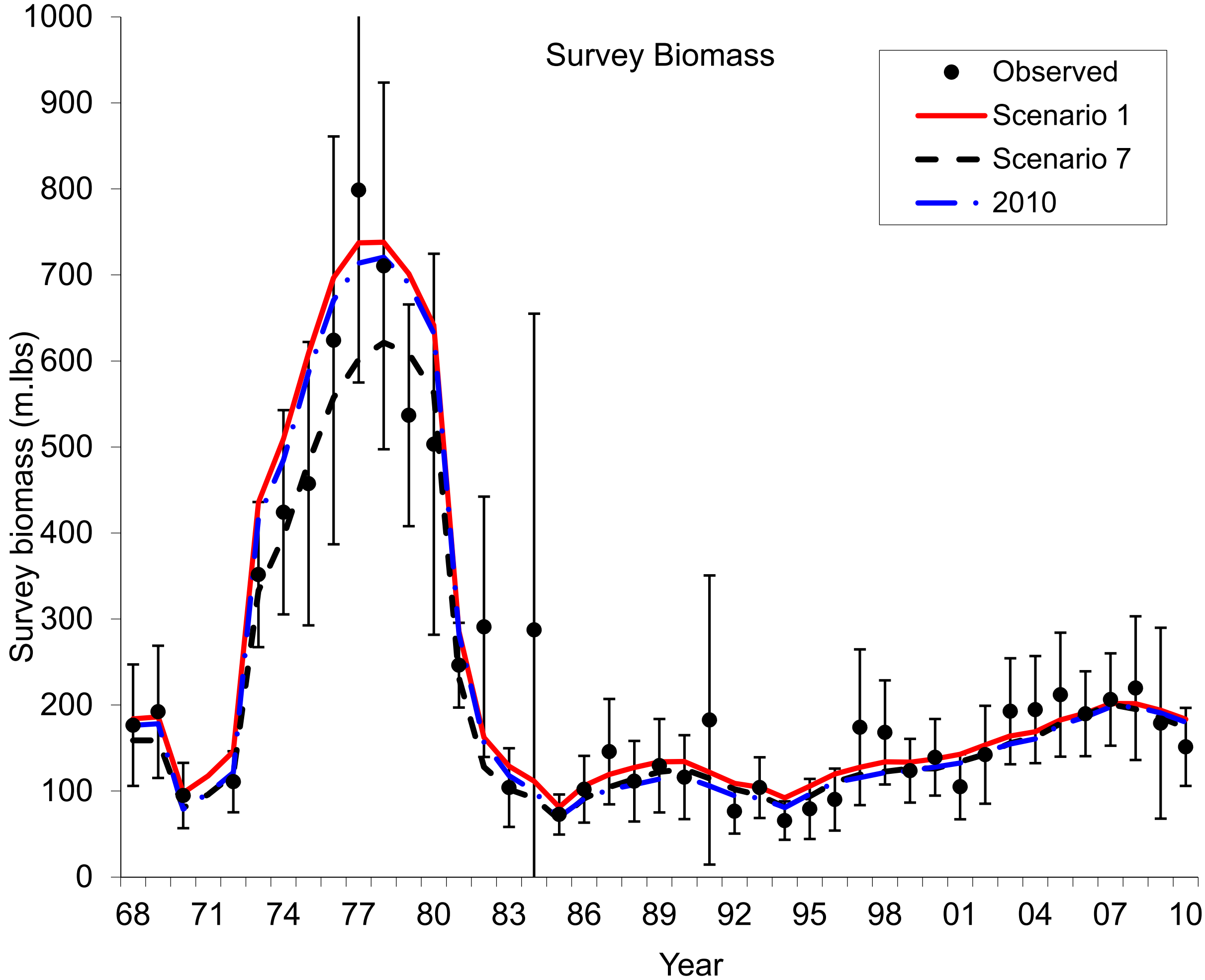


Figure 10a(7). Comparisons of area-swept estimates of total survey biomass and model prediction for scenarios 1 & 7. Scenario 0 is labeled as "2010". Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. The error bars are plus and minus 2 standard deviations.

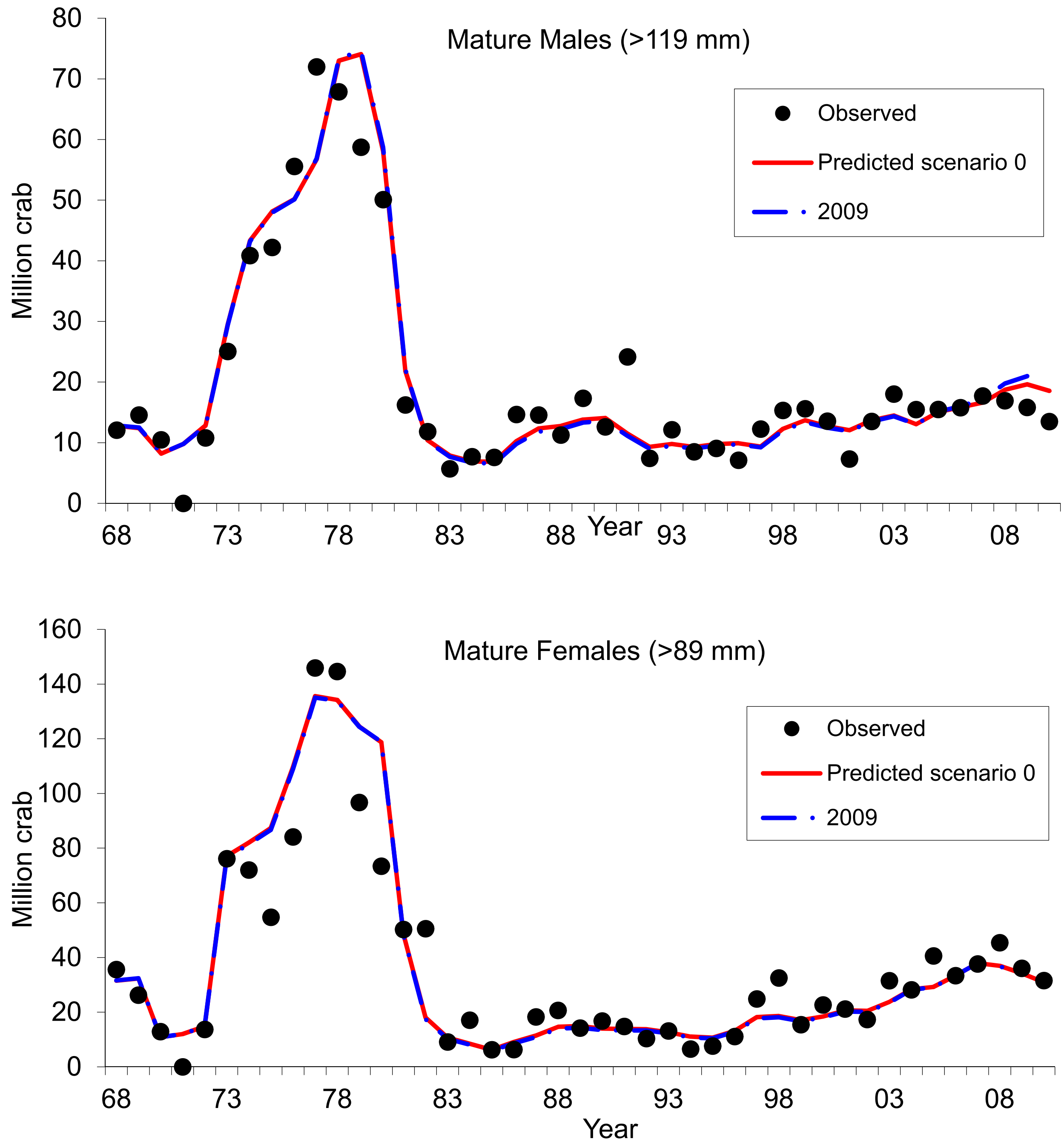
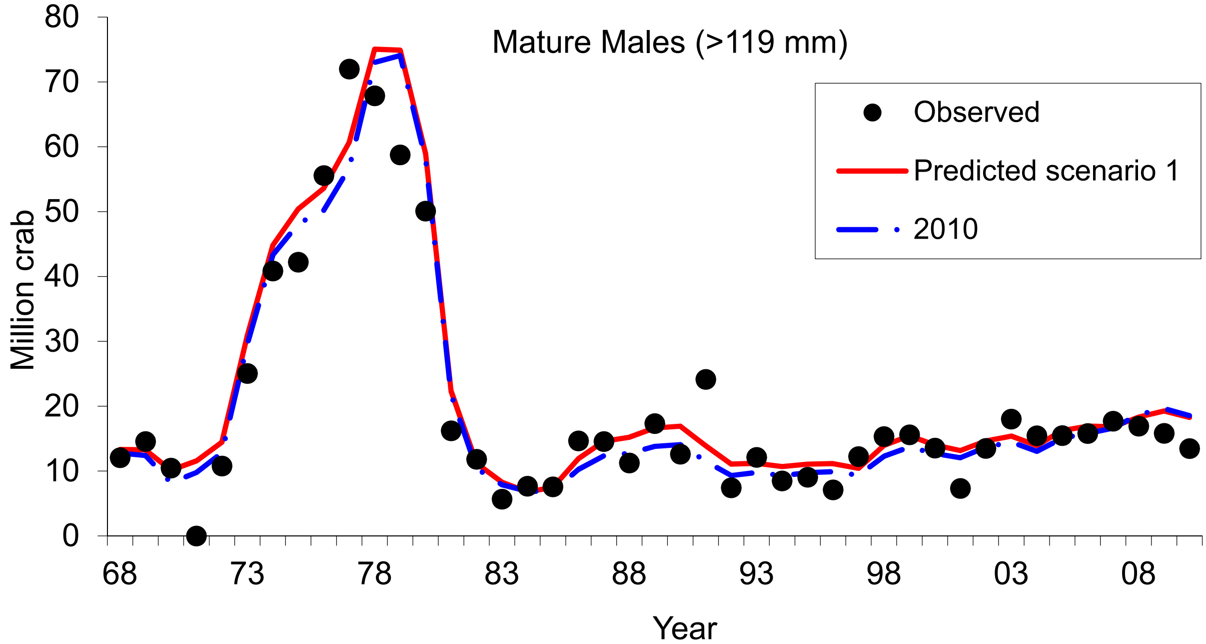


Figure 10b(0). Comparisons of area-swept estimates of mature male (>119 mm) and female (>89 mm) abundance and model prediction for scenario 0. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.



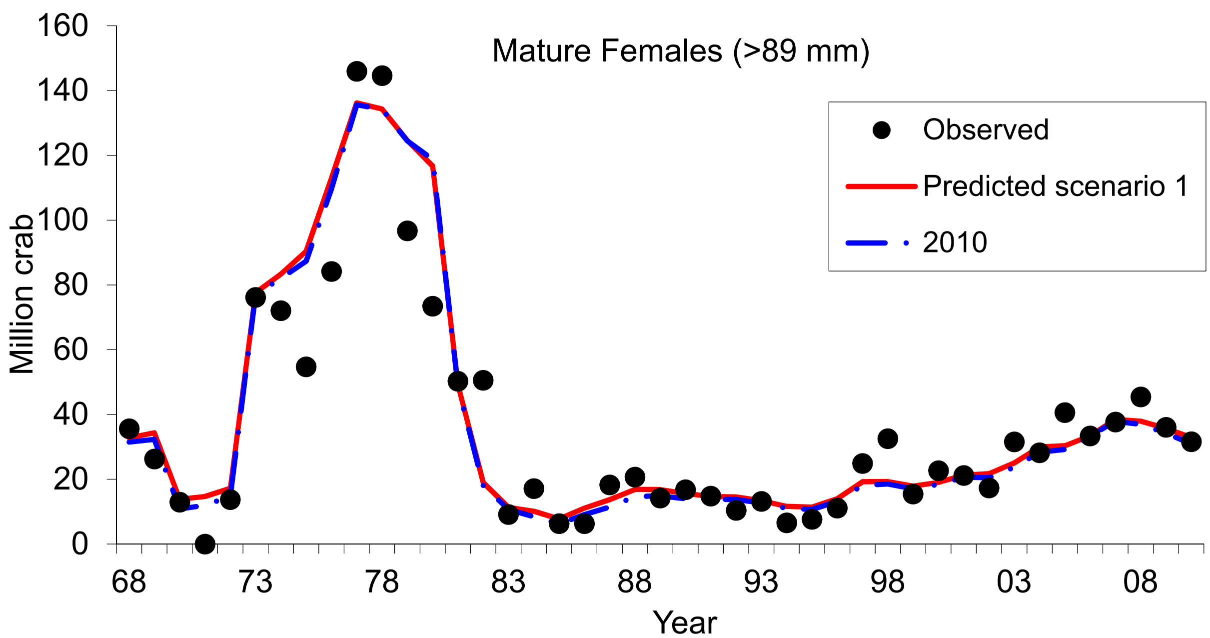


Figure 10b(1). Comparisons of area-swept estimates of mature male (>119 mm) and female (>89 mm) abundance and model prediction for scenario 1. Scenario 0 is labeled as "2010". Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

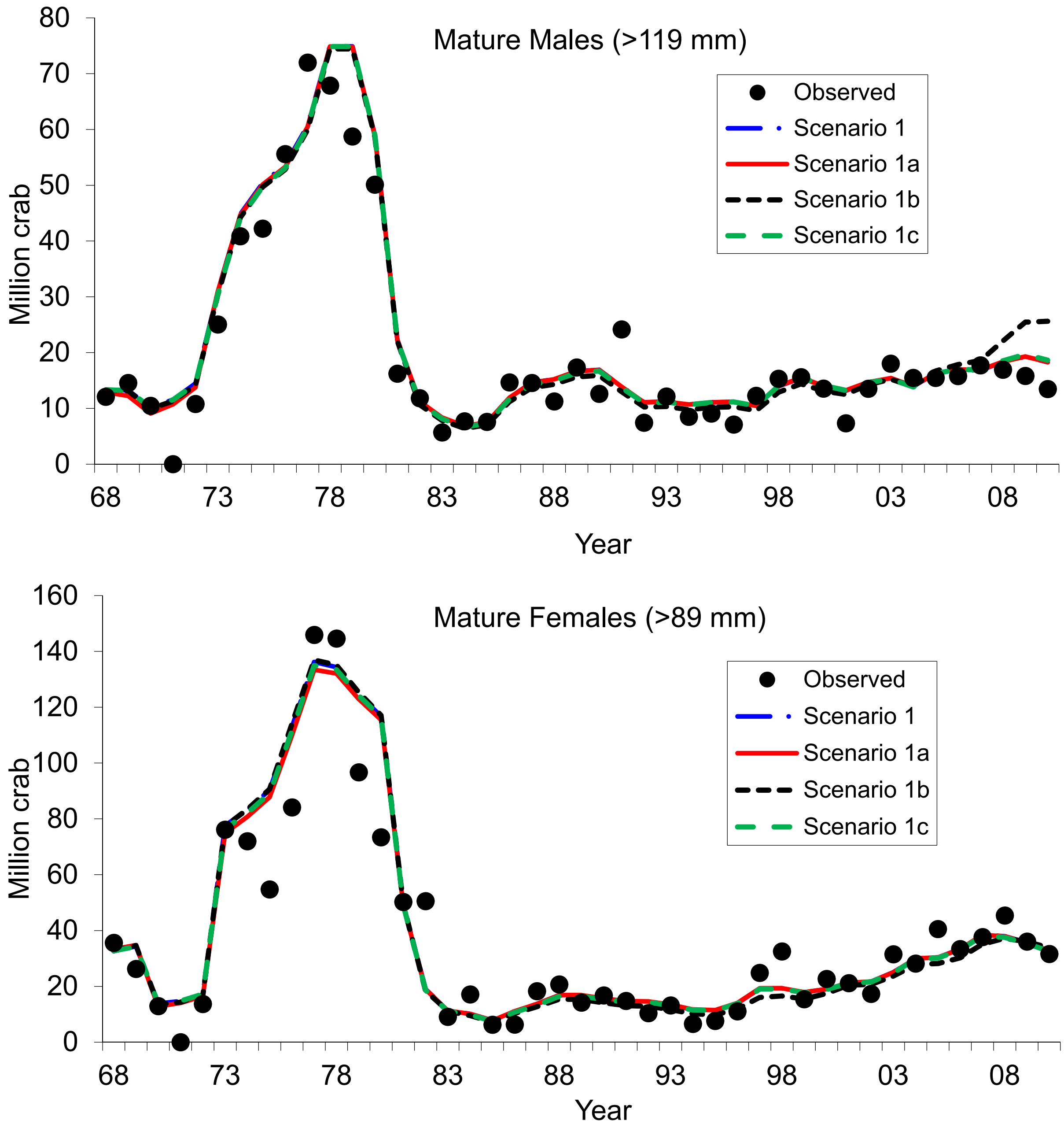
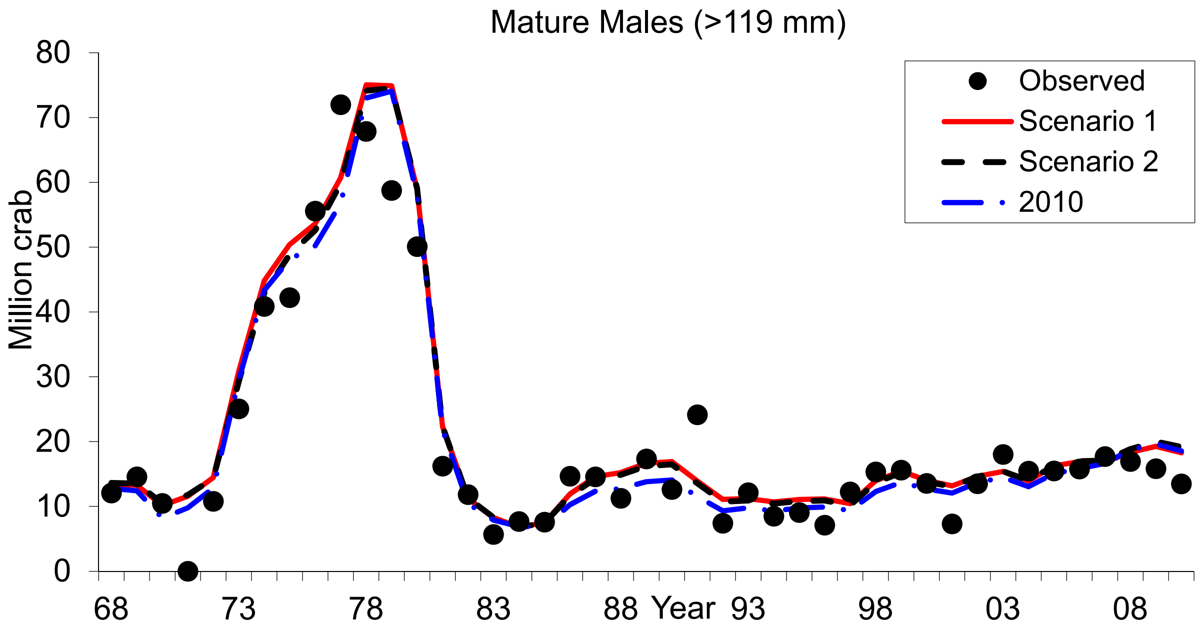


Figure 10b(1abc). Comparisons of area-swept estimates of mature male (>119 mm) and female (>89 mm) abundance and model prediction for scenarios 1, 1a, 1b and 1c. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.



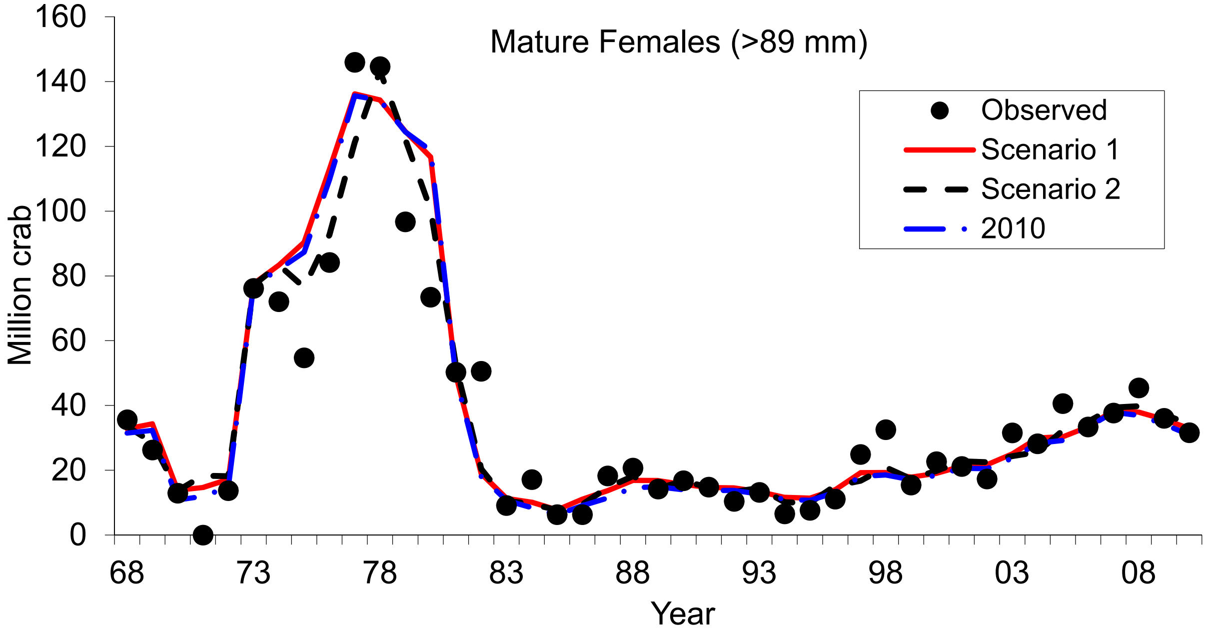
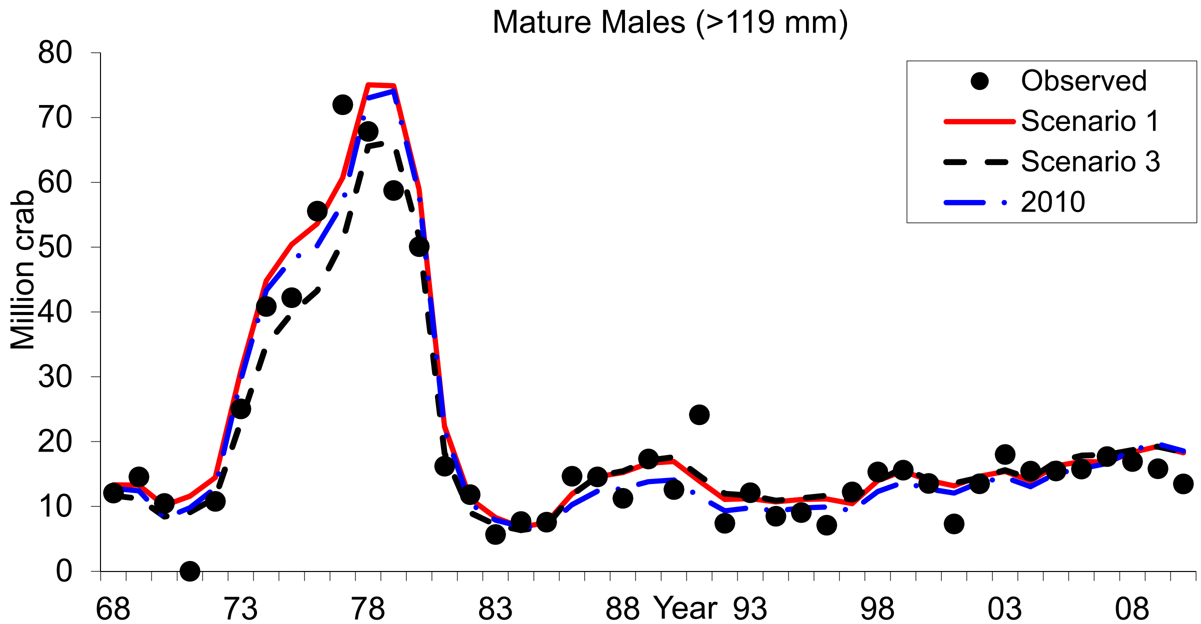


Figure 10b(2). Comparisons of area-swept estimates of mature male (>119 mm) and female (>89 mm) abundance and model prediction for scenarios 1&2. Scenario 0 is labeled as “2010”. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.



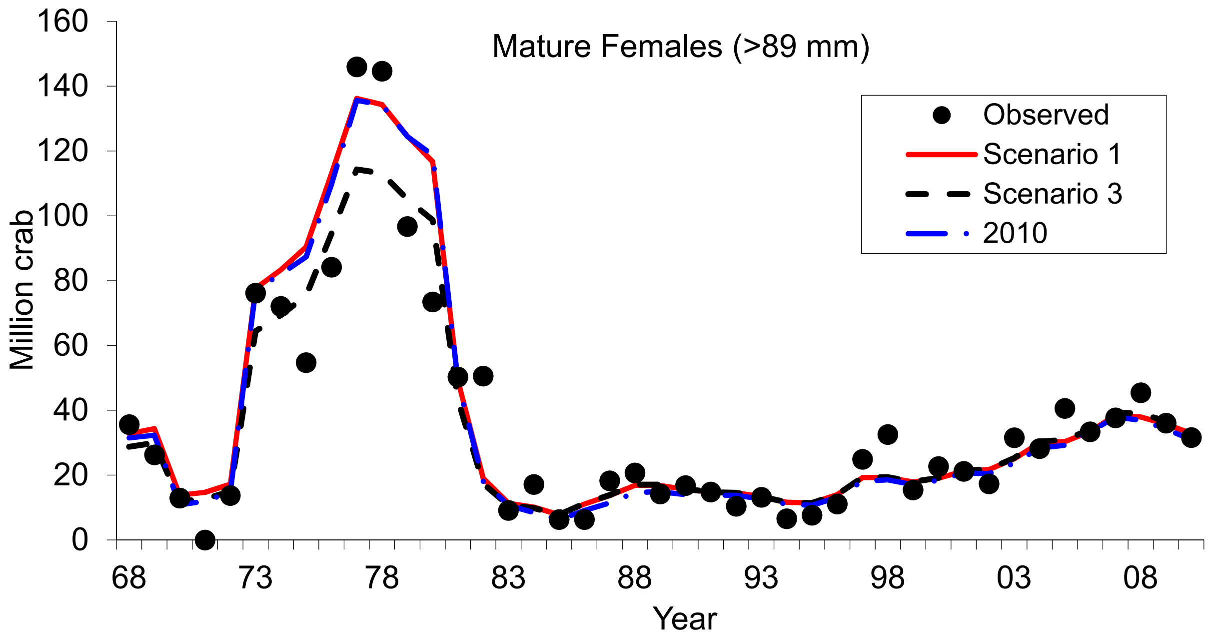
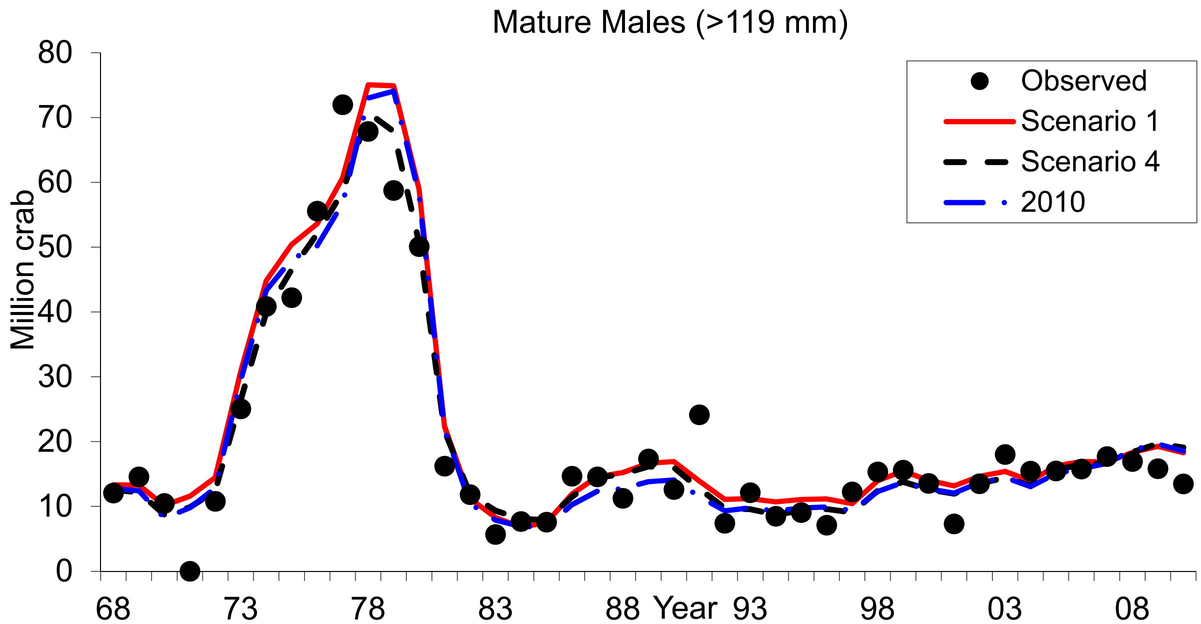


Figure 10b(3). Comparisons of area-swept estimates of mature male (>119 mm) and female (>89 mm) abundance and model prediction for scenarios 1&3. Scenario 0 is labeled as "2010". Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.



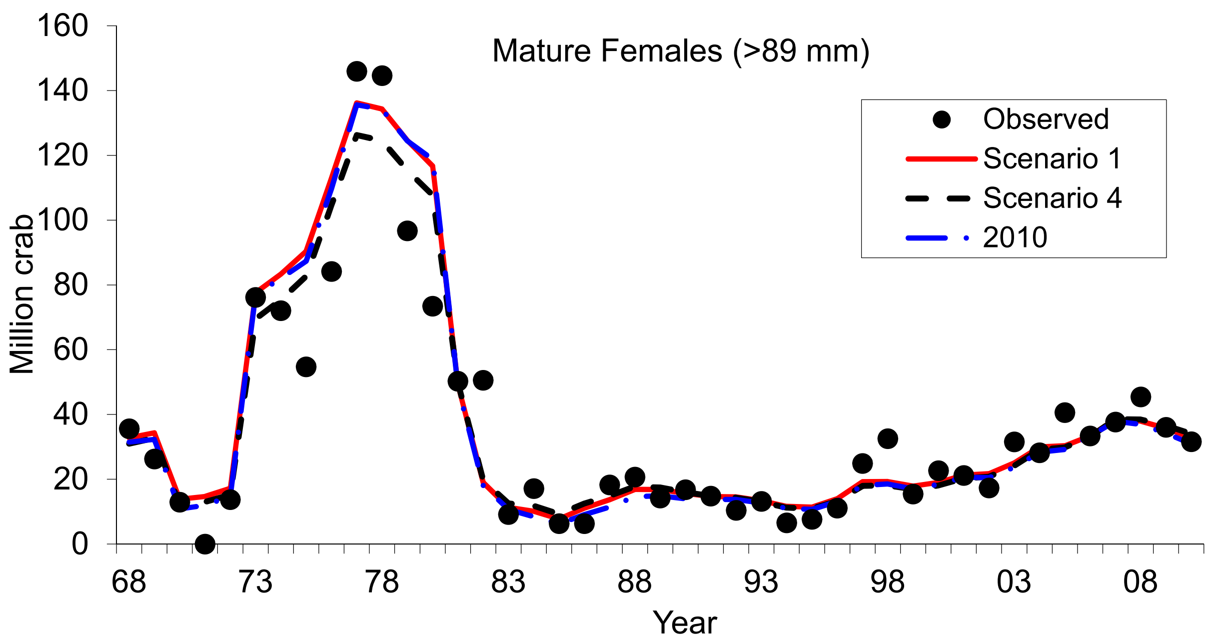


Figure 10b(4). Comparisons of area-swept estimates of mature male (>119 mm) and female (>89 mm) abundance and model prediction for scenarios 1&4. Scenario 0 is labeled as "2010". Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

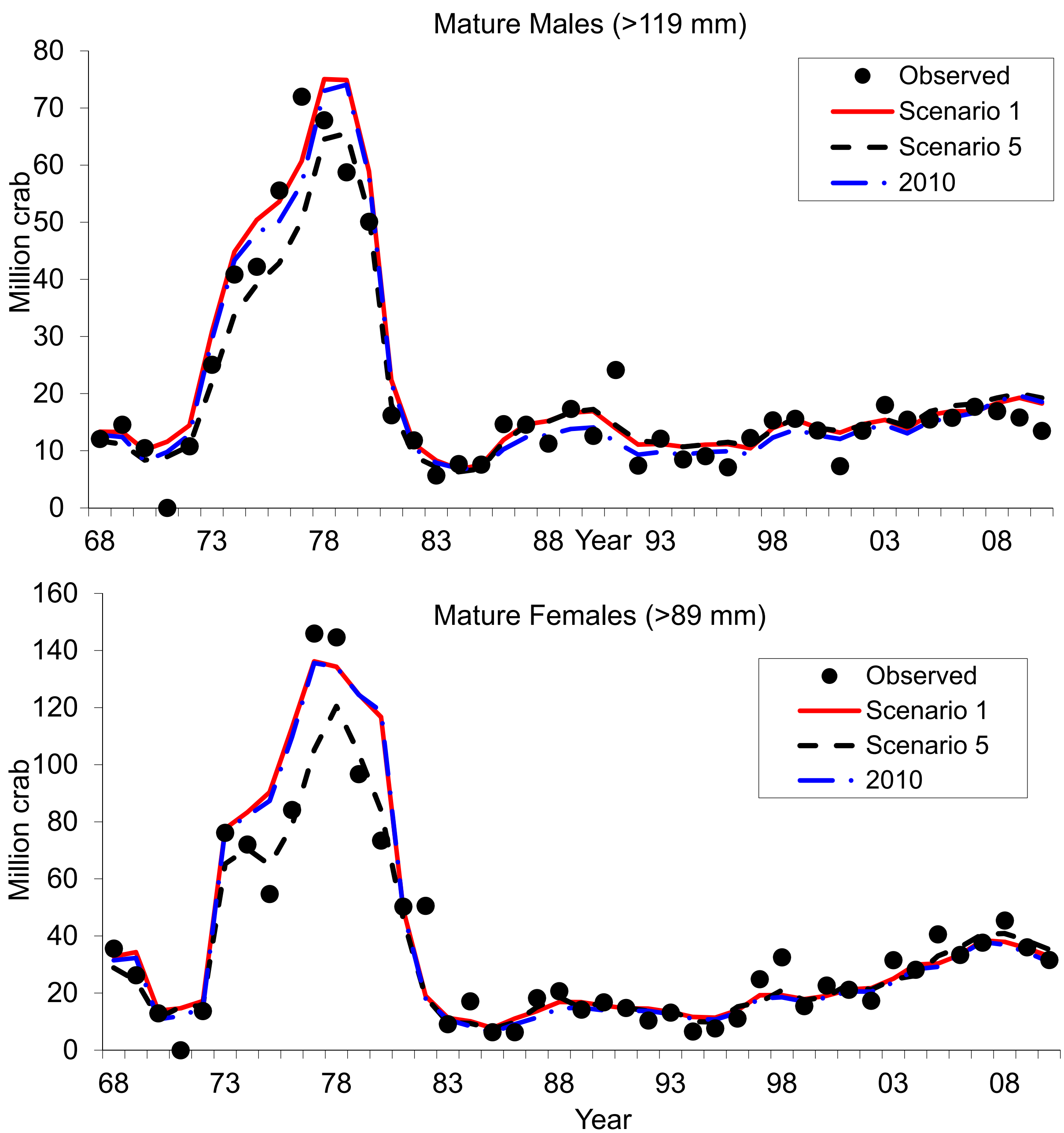


Figure 10b(5). Comparisons of area-swept estimates of mature male (>119 mm) and female (>89 mm) abundance and model prediction for scenarios 1&5. Scenario 0 is labeled as "2010". Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

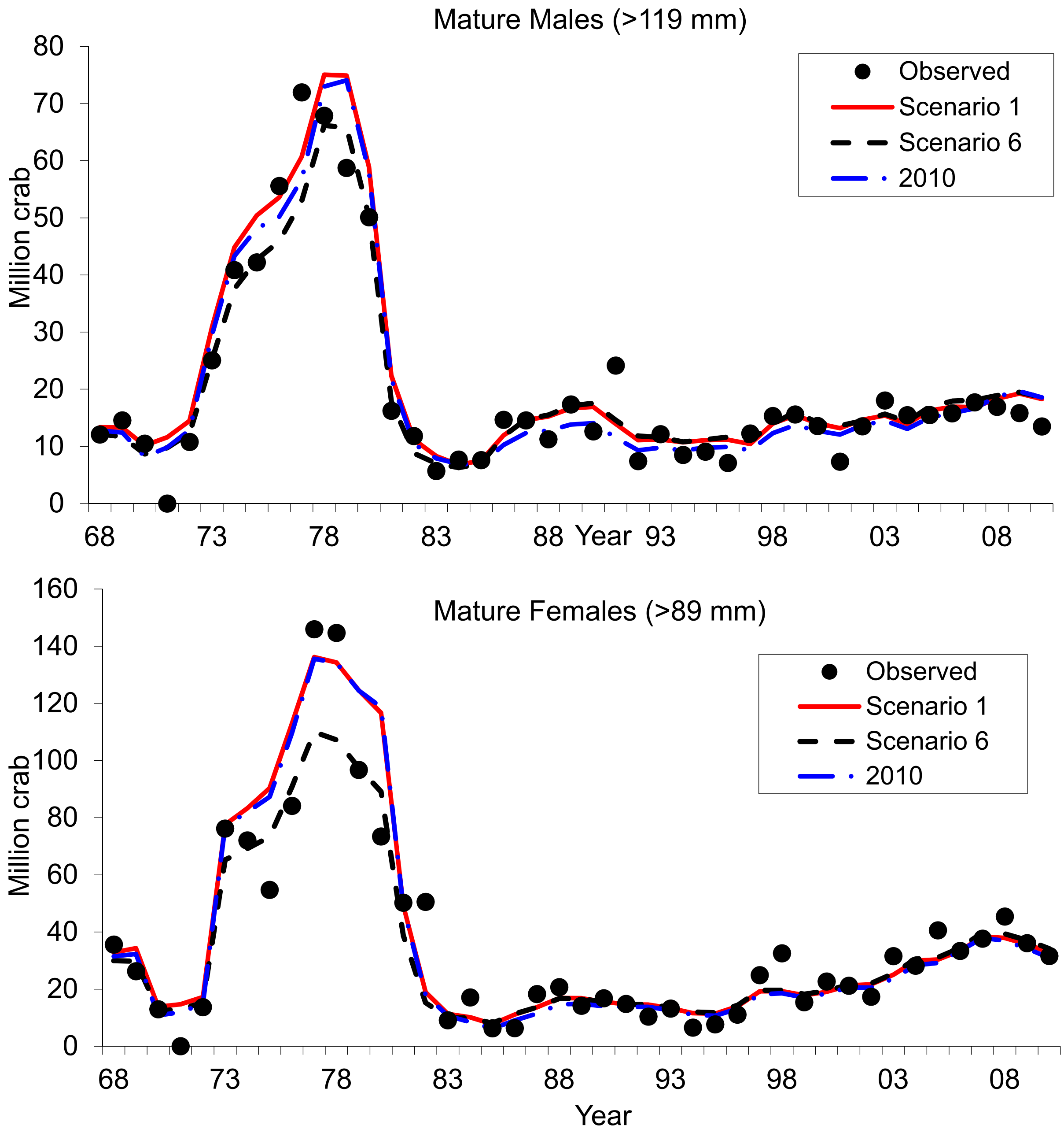


Figure 10b(6). Comparisons of area-swept estimates of mature male (>119 mm) and female (>89 mm) abundance and model prediction for scenarios 1&6. Scenario 0 is labeled as "2010". Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

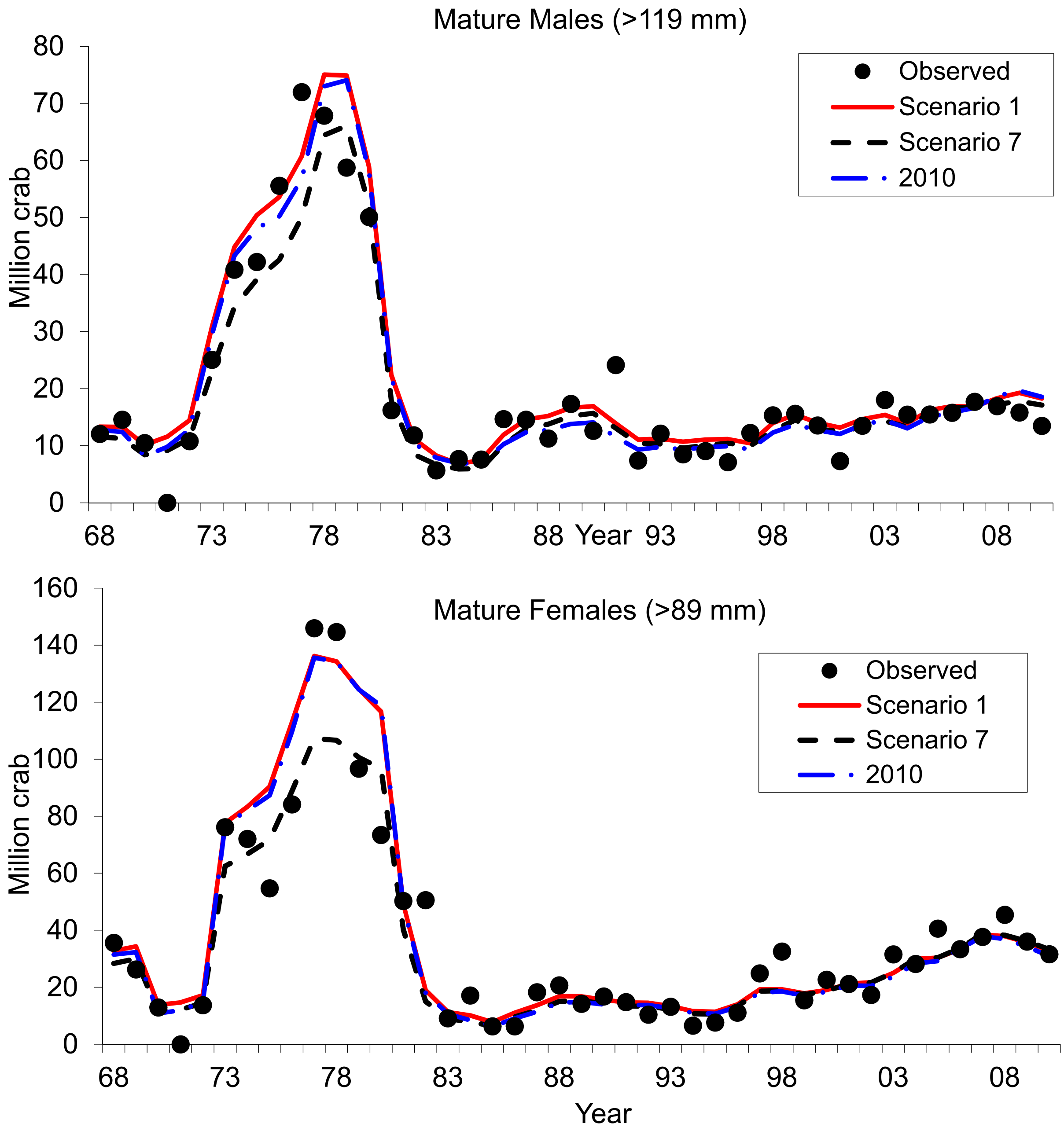


Figure 10b(7). Comparisons of area-swept estimates of mature male (>119 mm) and female (>89 mm) abundance and model prediction for scenarios 1&7. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

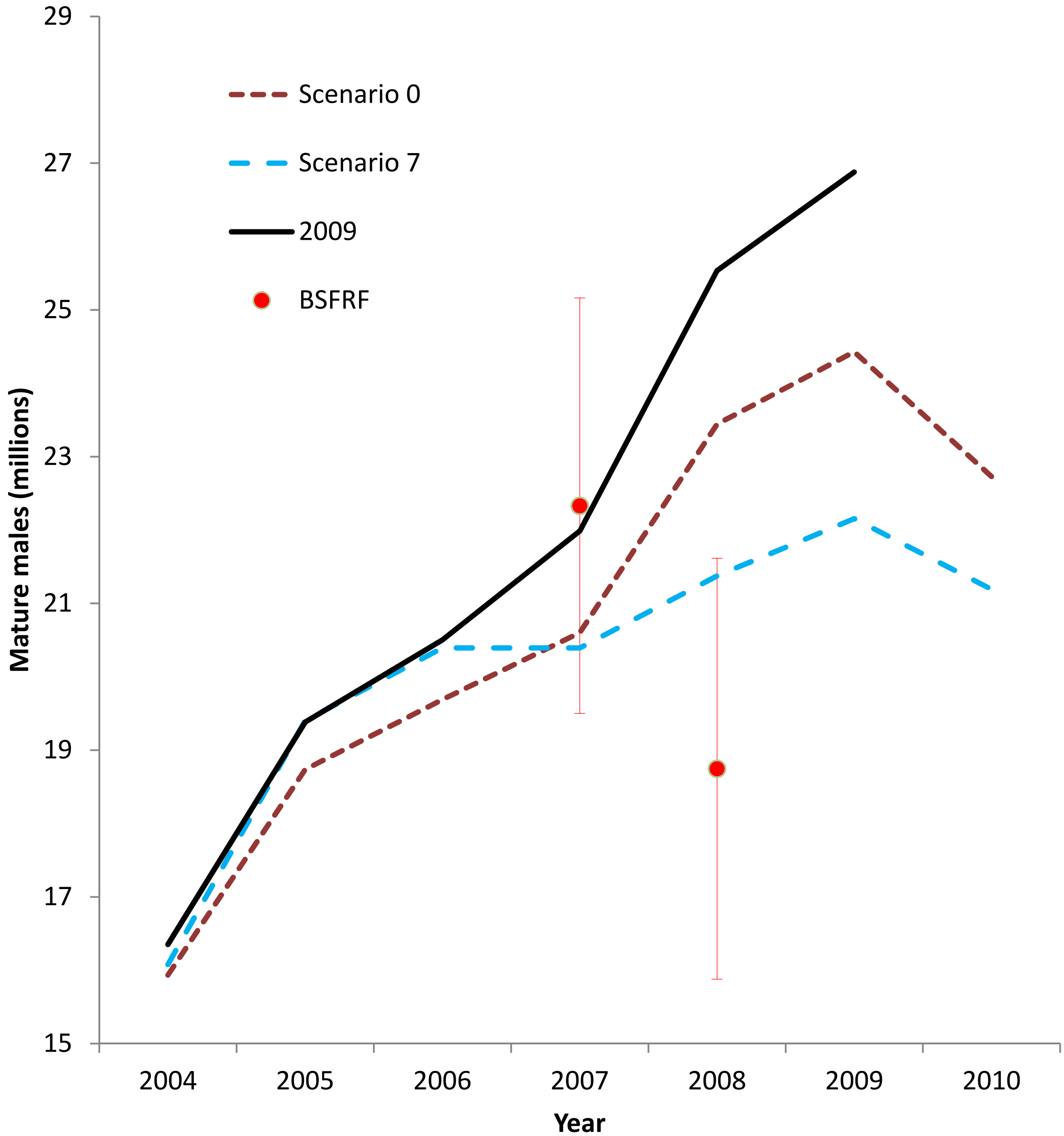


Figure 10c(0&7). Comparisons of total mature male abundance estimates by the BSFRF survey and the model for scenarios 0 & 7. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively. The error bars are plus and minus 2 standard deviations.

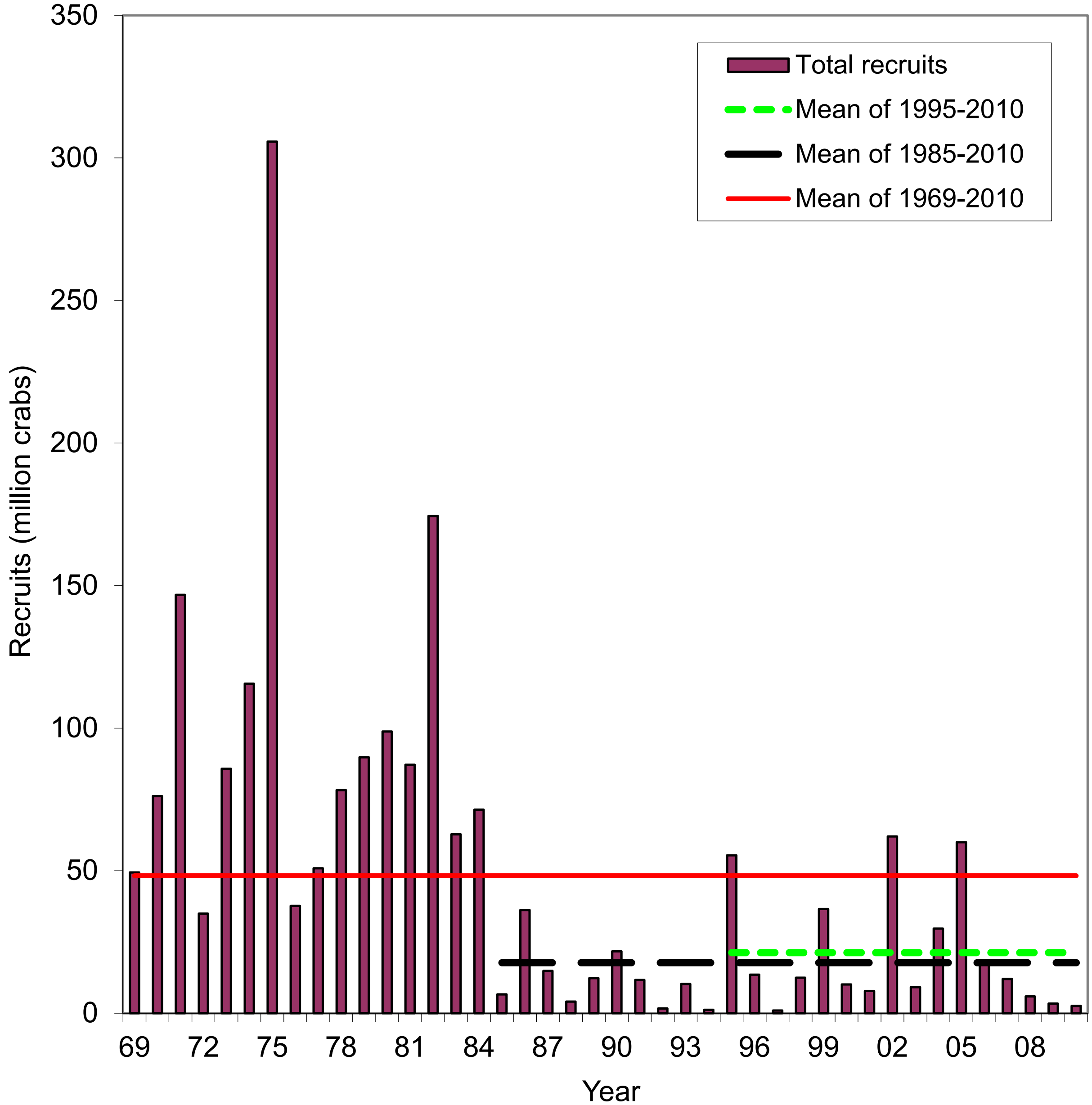


Figure 11(0). Estimated recruitment time series during 1969-2010 (occurred year) with scenario 0. Mean male recruits during 1995-2010 was used to estimate $B_{35\%}$.

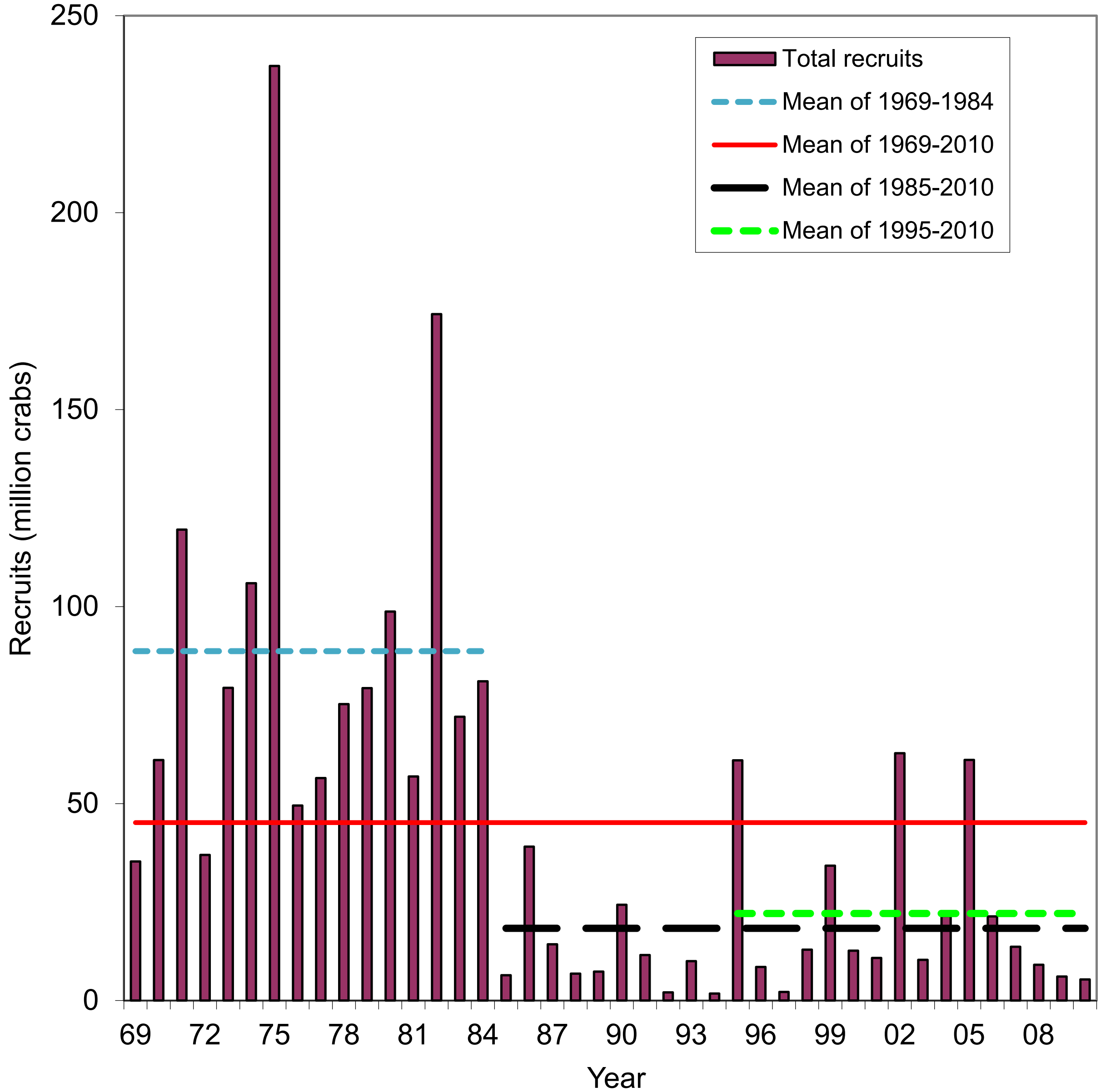


Figure 11(7). Estimated recruitment time series during 1969-2010 (occurred year) with scenario 7. Mean male recruits during 1995-2010 was used to estimate $B_{35\%}$.

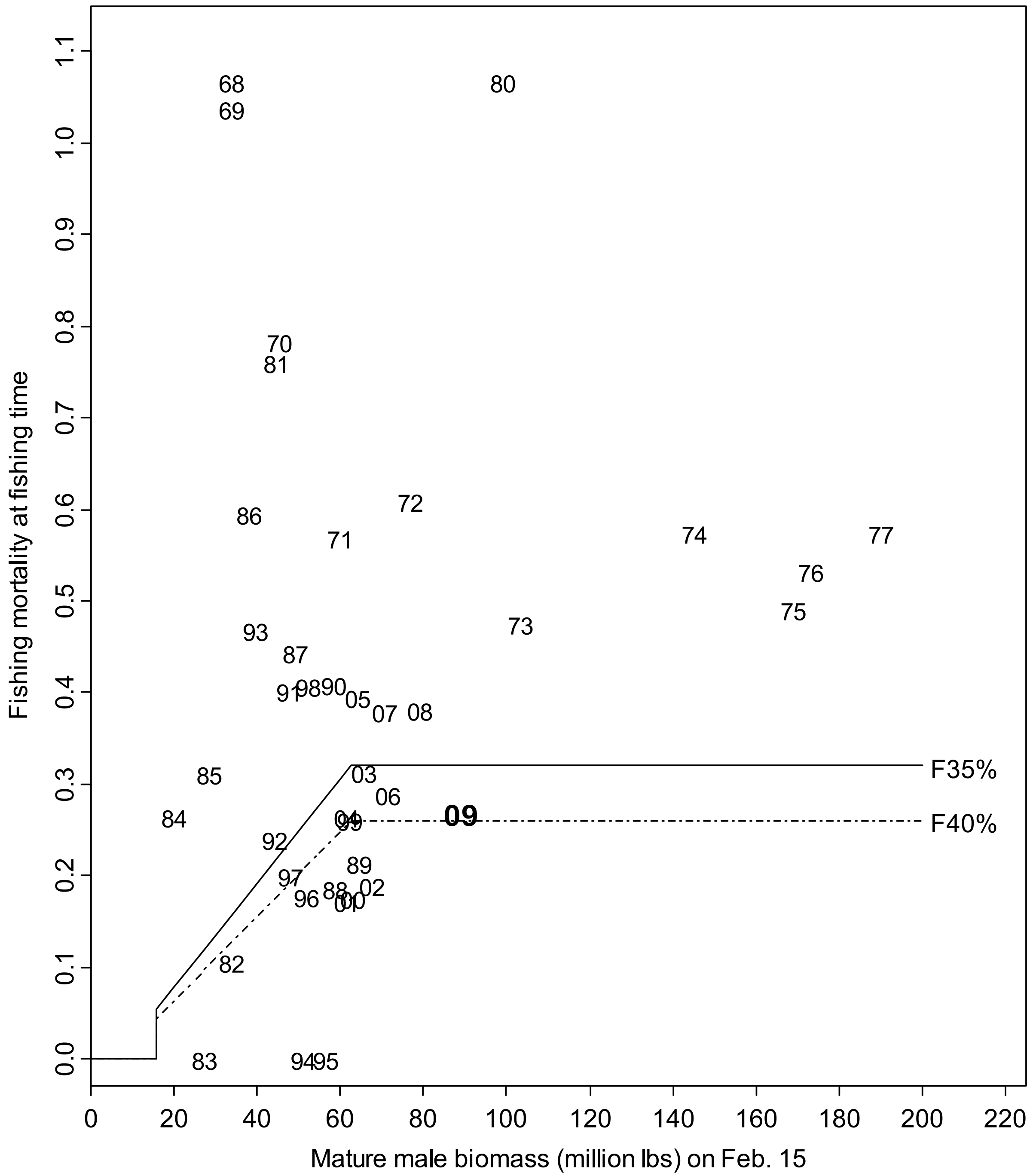


Figure 12(0). Relationships between full fishing mortalities for the directed pot fishery and mature male biomass on Feb. 15 during 1968-2009 under scenario 0. Average of recruitment from 1995 to 2010 was used to estimate B_{MSY}. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

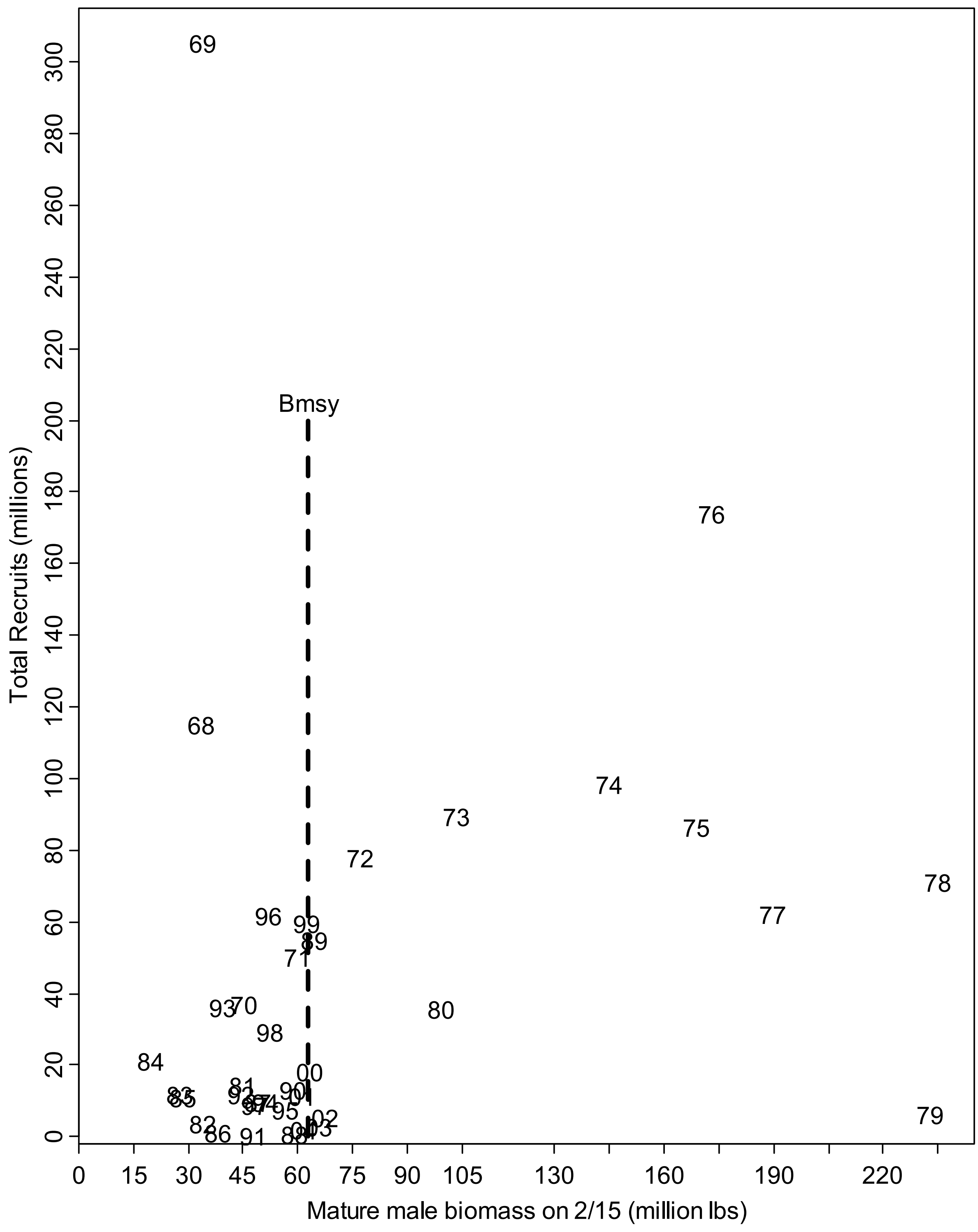


Figure 13a(0). Relationships between mature male biomass on Feb. 15 and total recruits at age 5 (i.e., 6-year time lag) for Bristol Bay red king crab with pot handling mortality rate to be 0.2 under scenario 0. Numerical labels are years of mating, and the vertical dotted lines are the estimated $B_{35\%}$ based on three different recruitment levels.

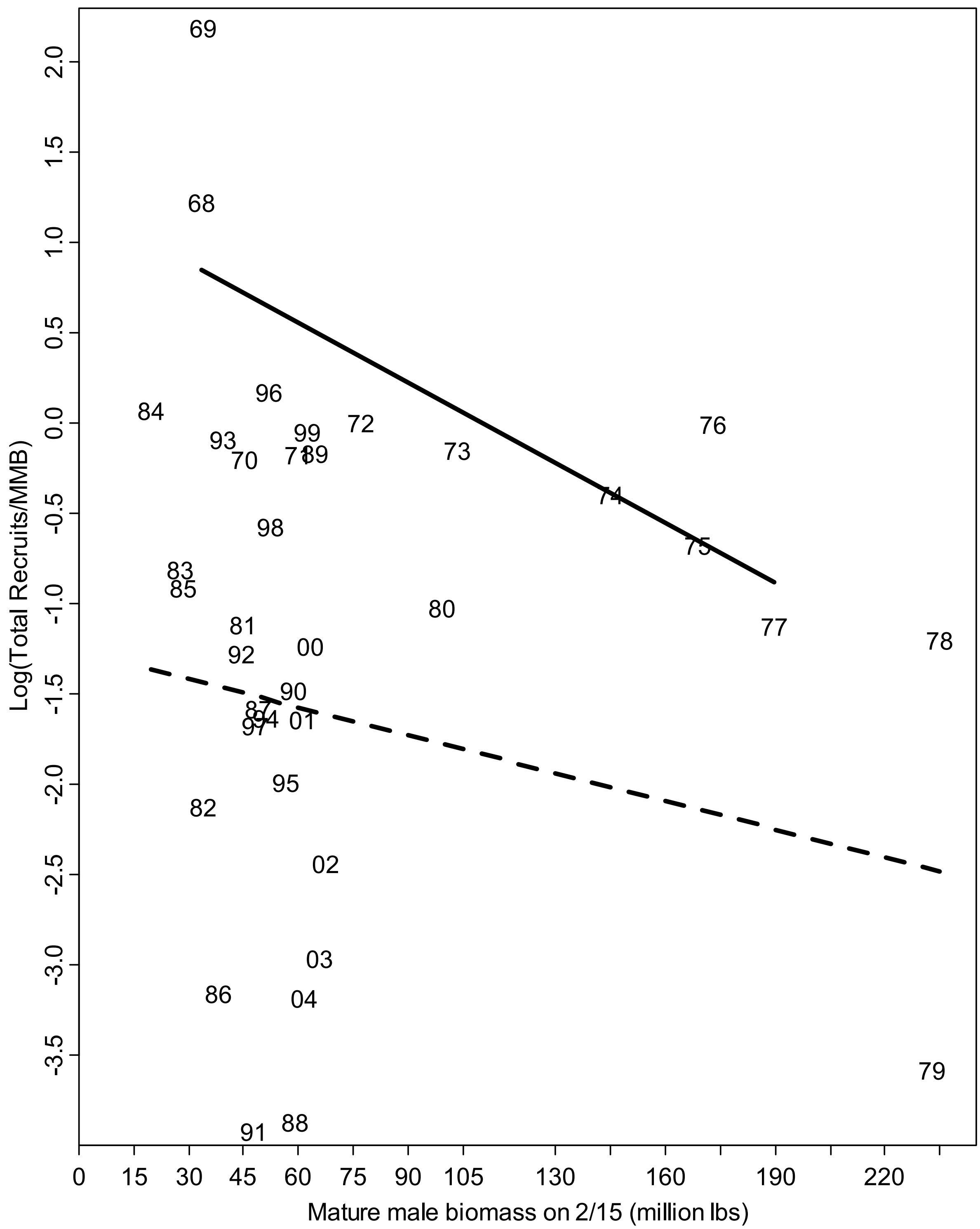


Figure 13b(0). Relationships between log recruitment per mature male biomass and mature male biomass on Feb. 15 for Bristol Bay red king crab with pot handling mortality rate to be 0.2 under scenario 0. Numerical labels are years of mating, the solid line is the regression line for data of 1968-1977, and the dotted line is the regression line for data of 1978-2004.

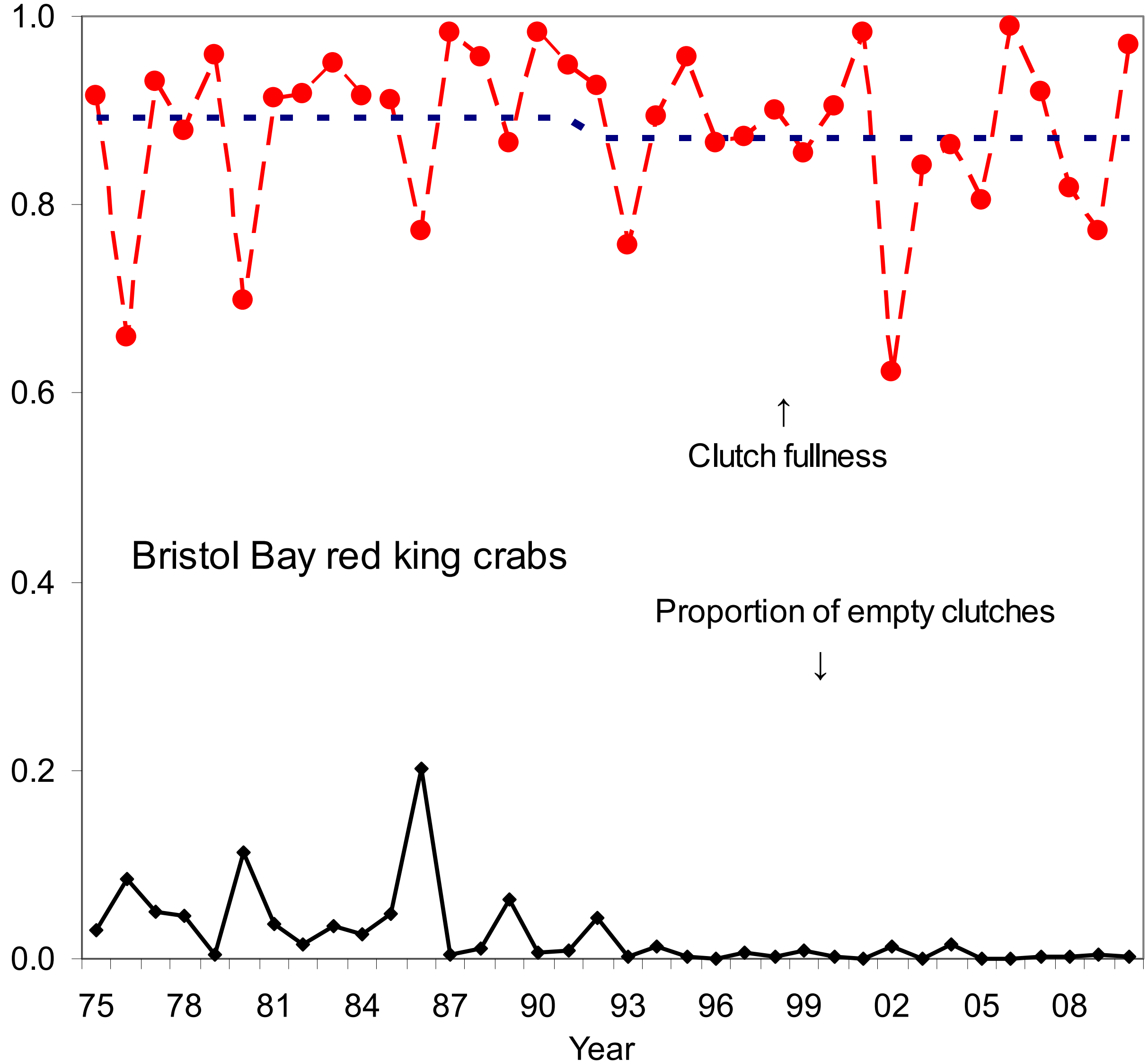


Figure 14. Average clutch fullness and proportion of empty clutches of newshell (shell conditions 1 and 2) mature female crabs >89 mm CL from 1975 to 2010 from survey data. Oldshell females were excluded.

Figure 15a(0). Observed and predicted catch mortality biomass under scenario 0. Mortality biomass is equal to caught biomass times a handling mortality rate. Pot handling mortality rate is 0.2.

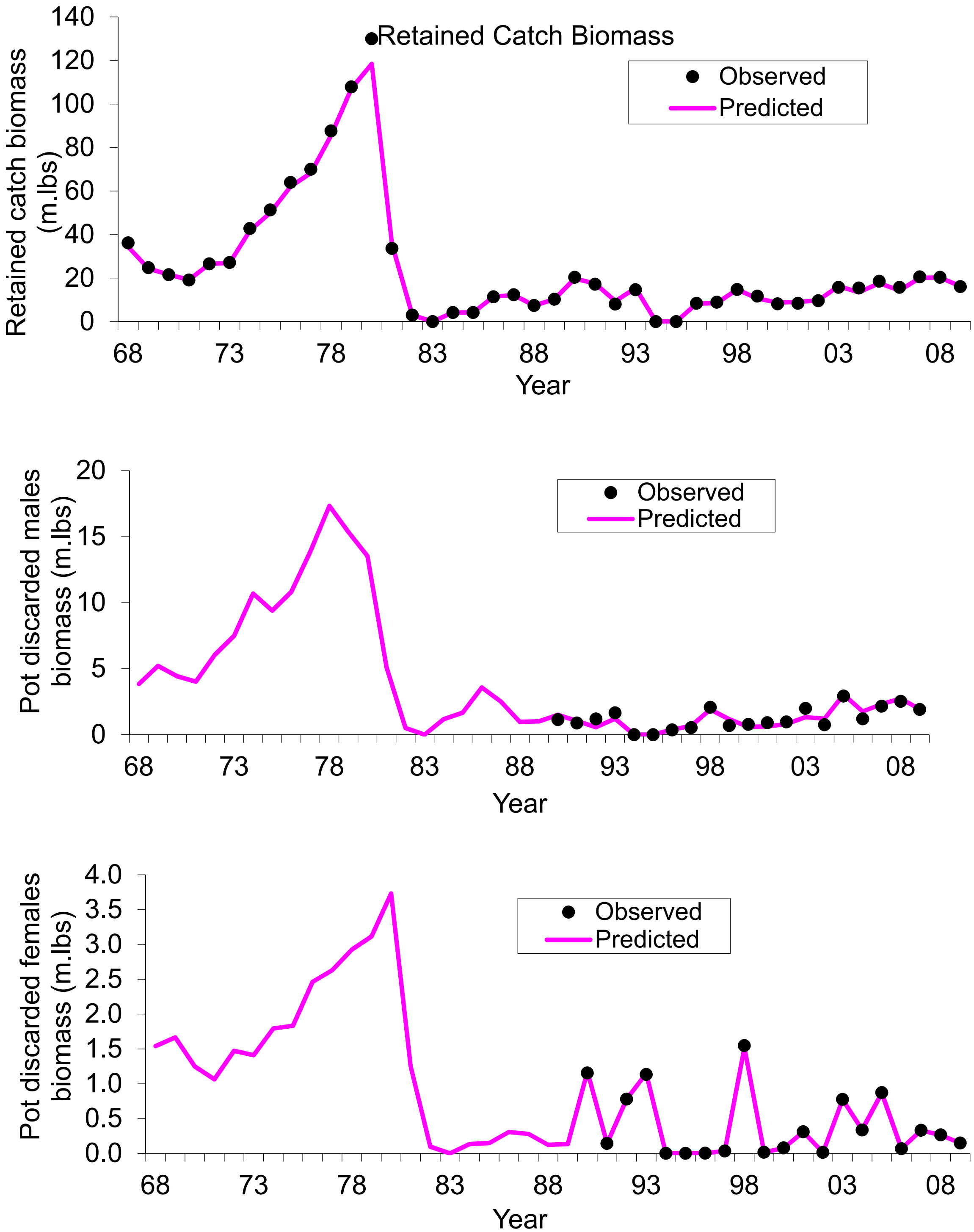


Figure 15a(1). Observed and predicted catch mortality biomass under scenario 1. Mortality biomass is equal to caught biomass times a handling mortality rate. Pot handling mortality rate is 0.2.

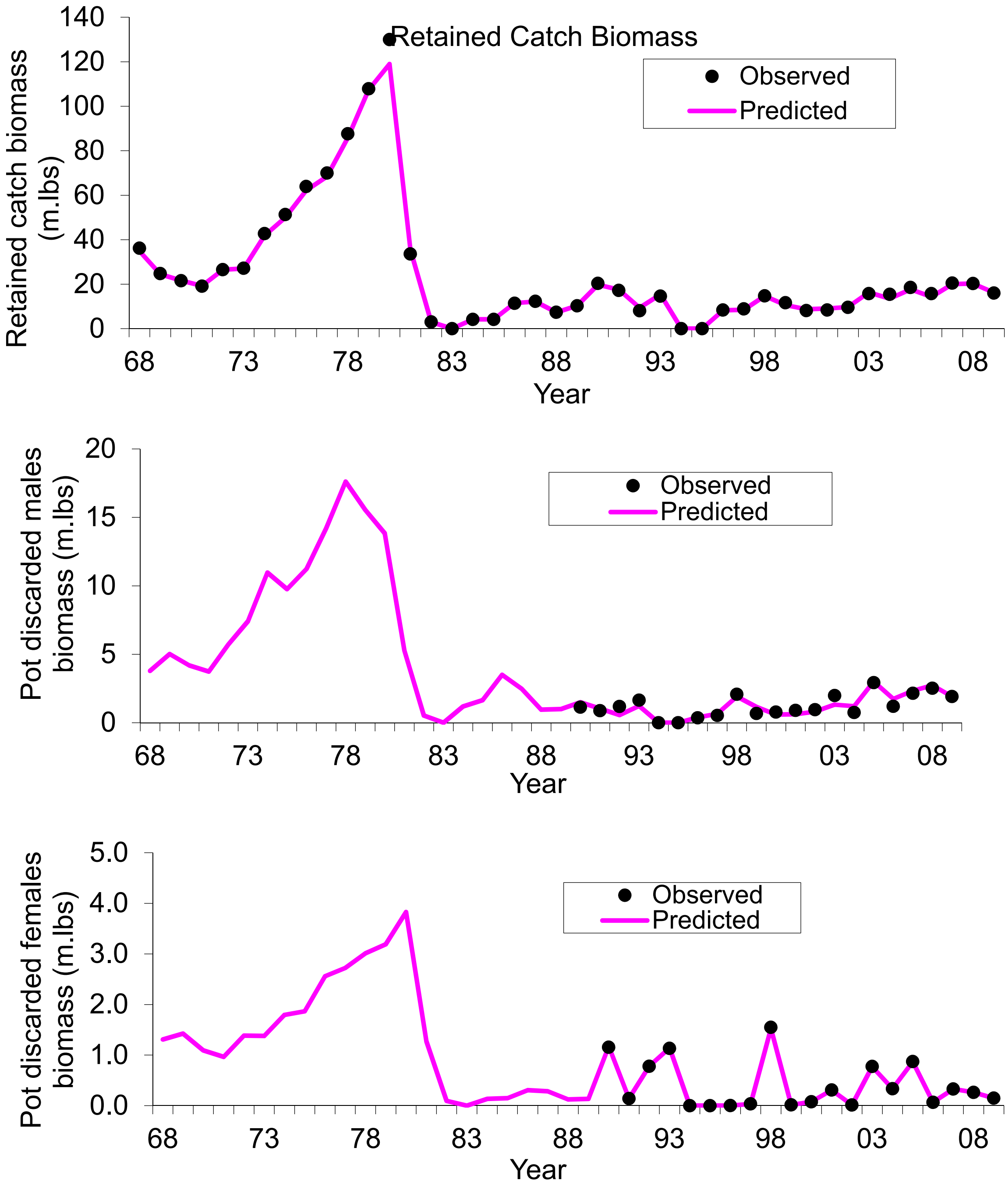


Figure 15a(2). Observed and predicted catch mortality biomass under scenario 2. Mortality biomass is equal to caught biomass times a handling mortality rate. Pot handling mortality rate is 0.2.

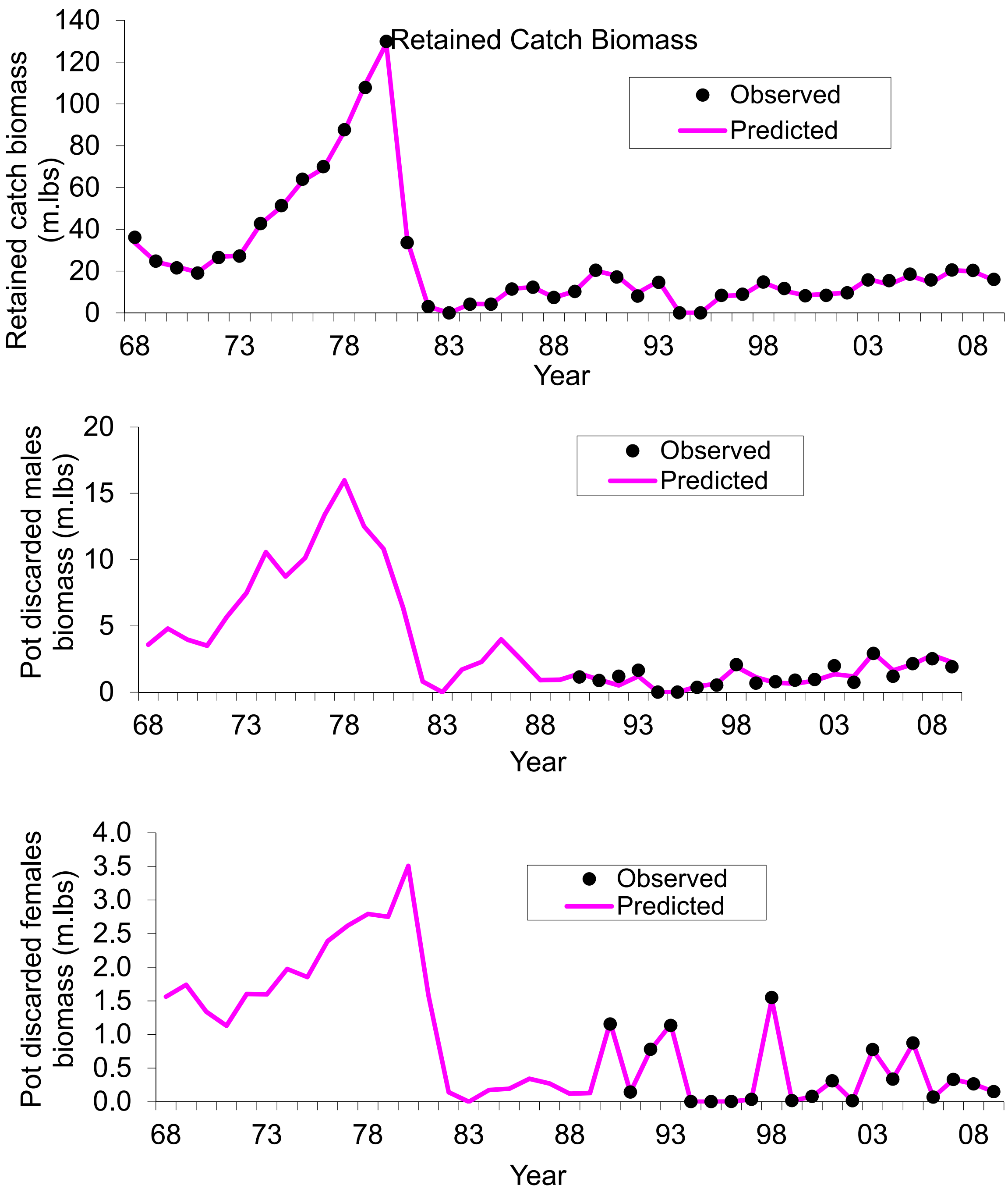


Figure 15a(3). Observed and predicted catch mortality biomass under scenario 3. Mortality biomass is equal to caught biomass times a handling mortality rate. Pot handling mortality rate is 0.2.

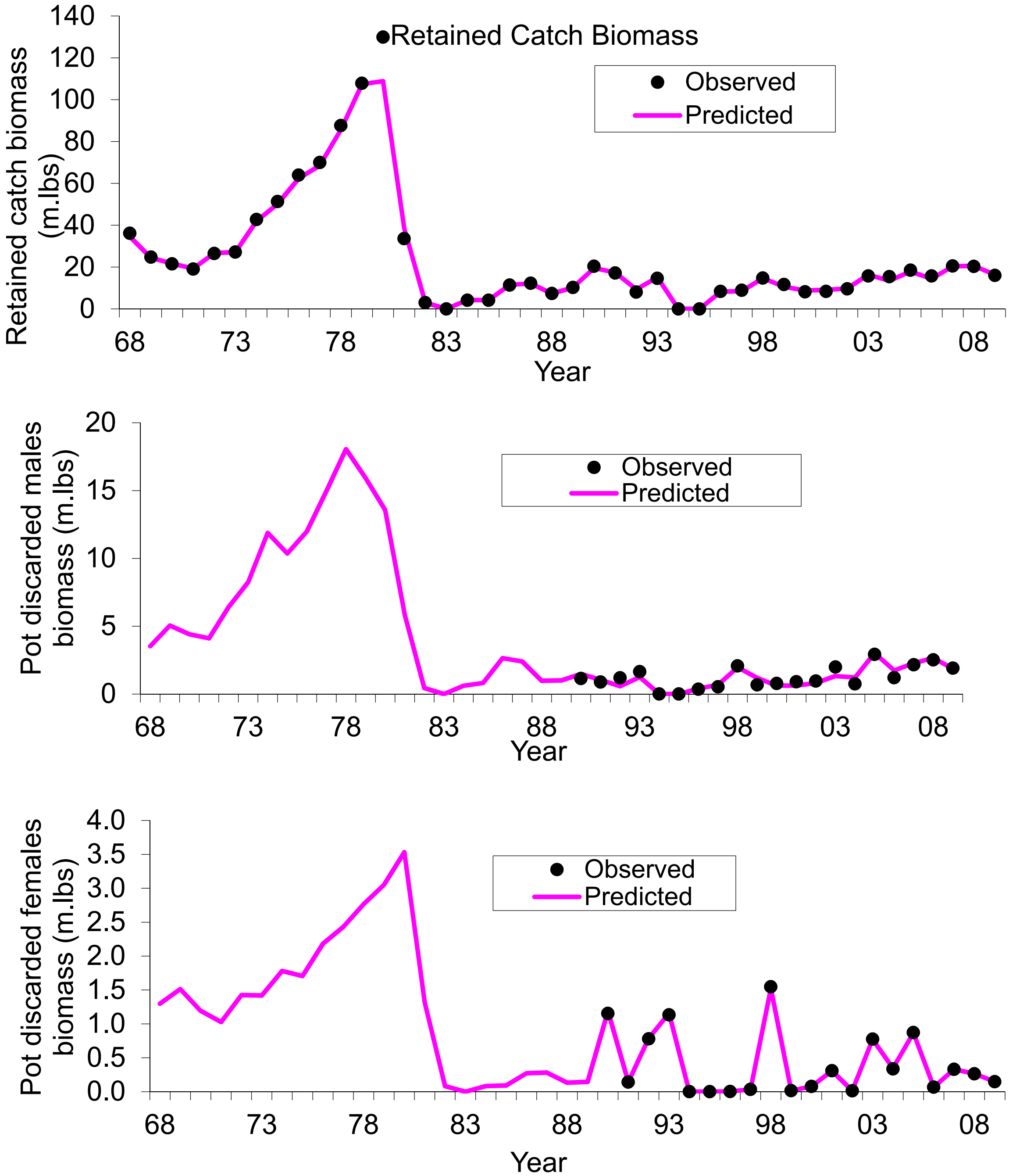
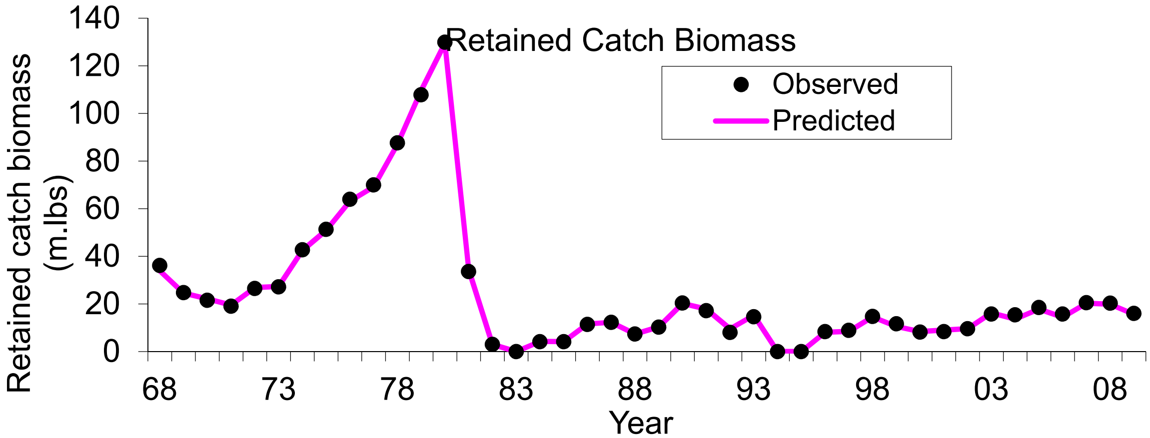
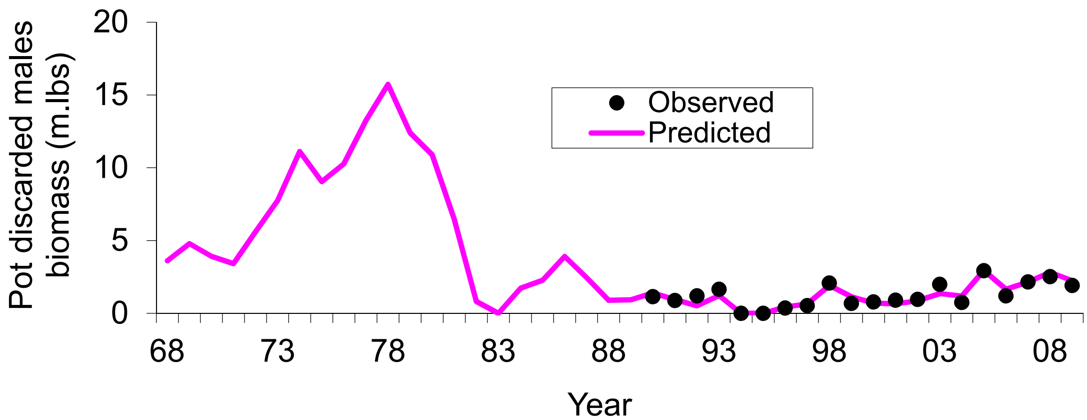


Figure 15a(4). Observed and predicted catch mortality biomass under scenario 4. Mortality biomass is equal to caught biomass times a handling mortality rate. Pot handling mortality rate is 0.2.





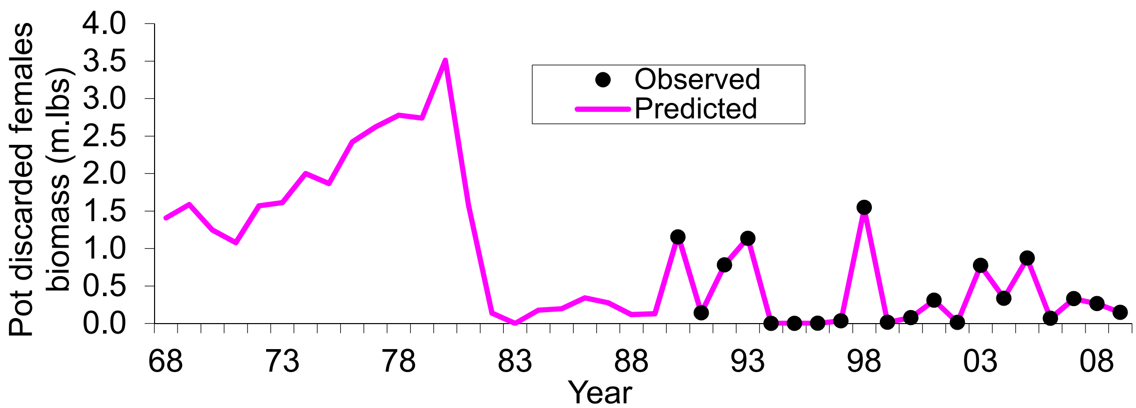


Figure 15a(5). Observed and predicted catch mortality biomass under scenario 5. Mortality biomass is equal to caught biomass times a handling mortality rate. Pot handling mortality rate is 0.2.

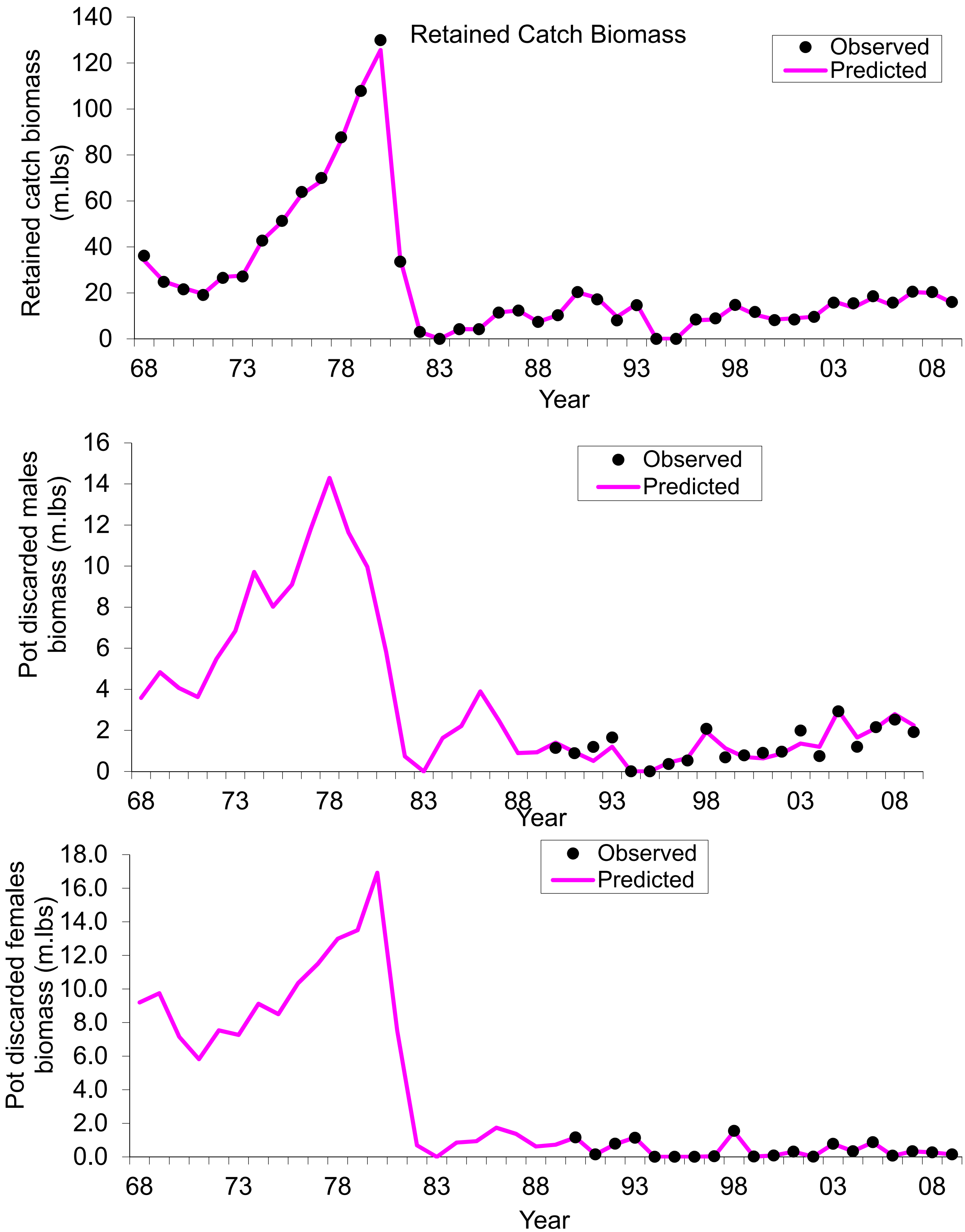
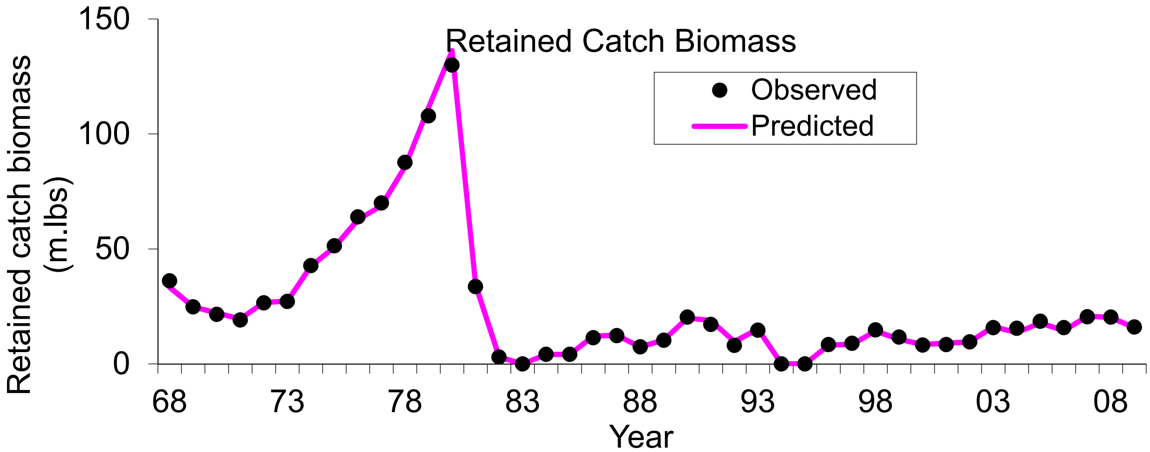
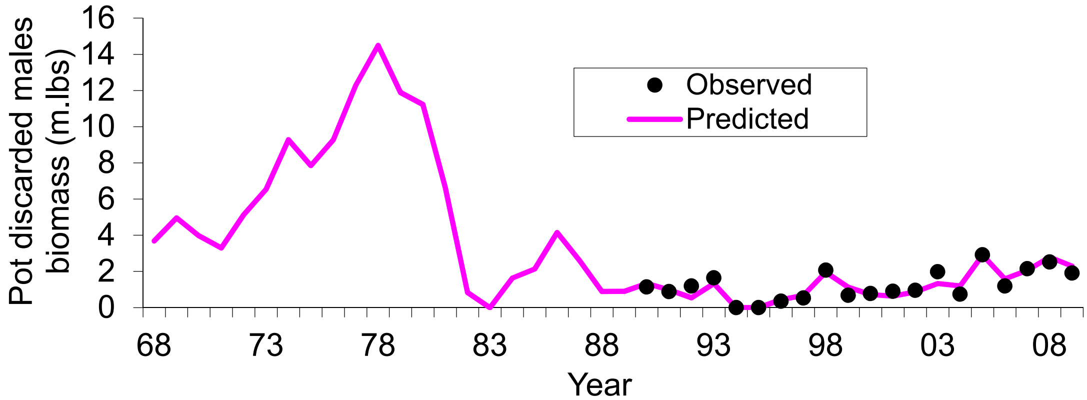


Figure 15a(6). Observed and predicted catch mortality biomass under scenario 6. Mortality biomass is equal to caught biomass times a handling mortality rate. Pot handling mortality rate is 0.2.





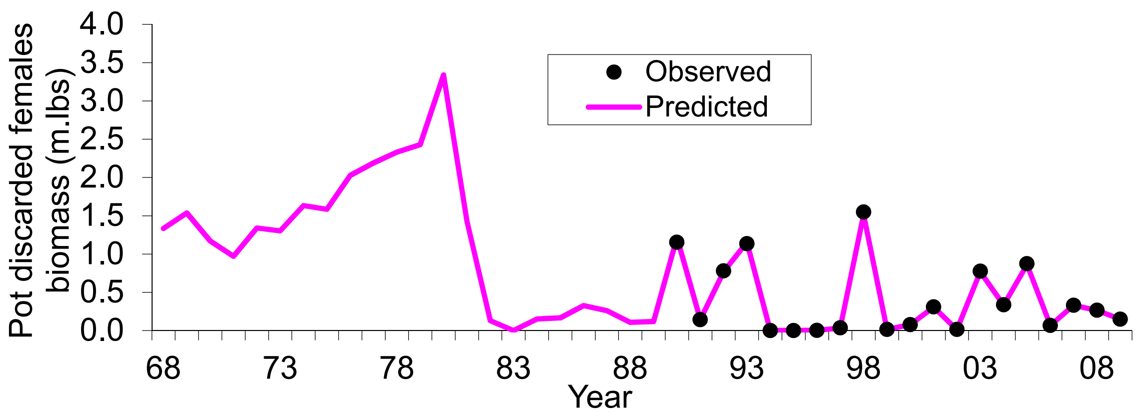
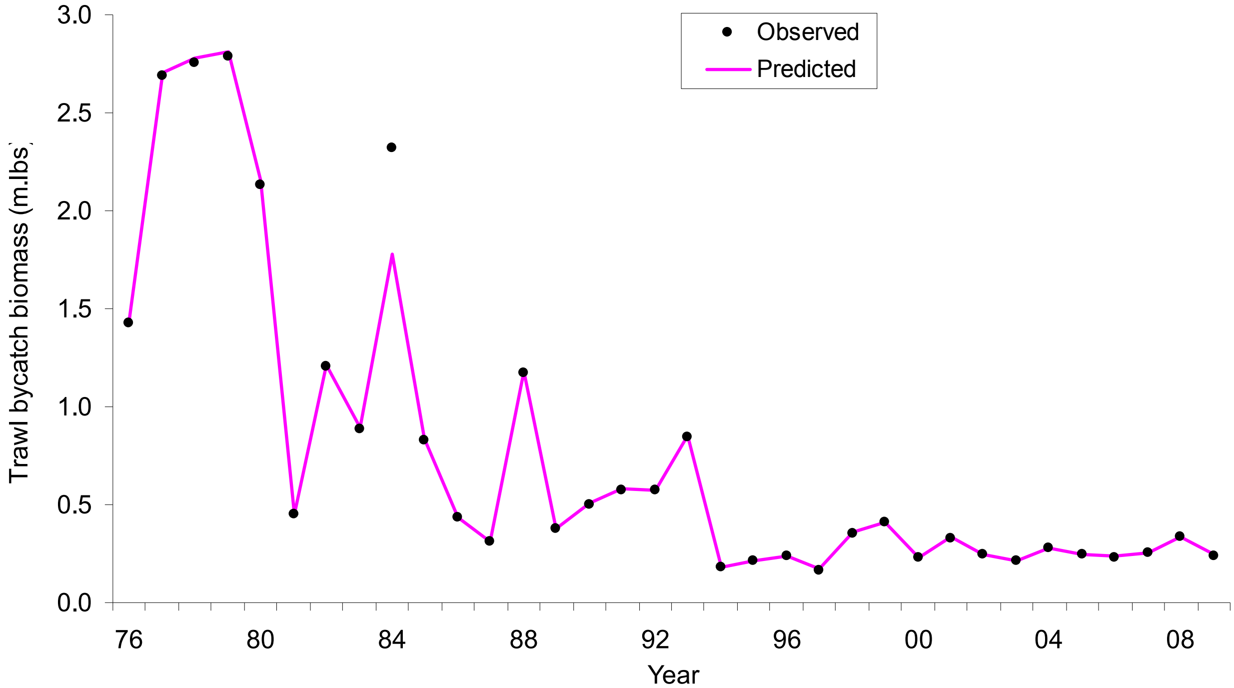


Figure 15a(7). Observed and predicted catch mortality biomass under scenario 7. Mortality biomass is equal to caught biomass times a handling mortality rate. Pot handling mortality rate is 0.2.



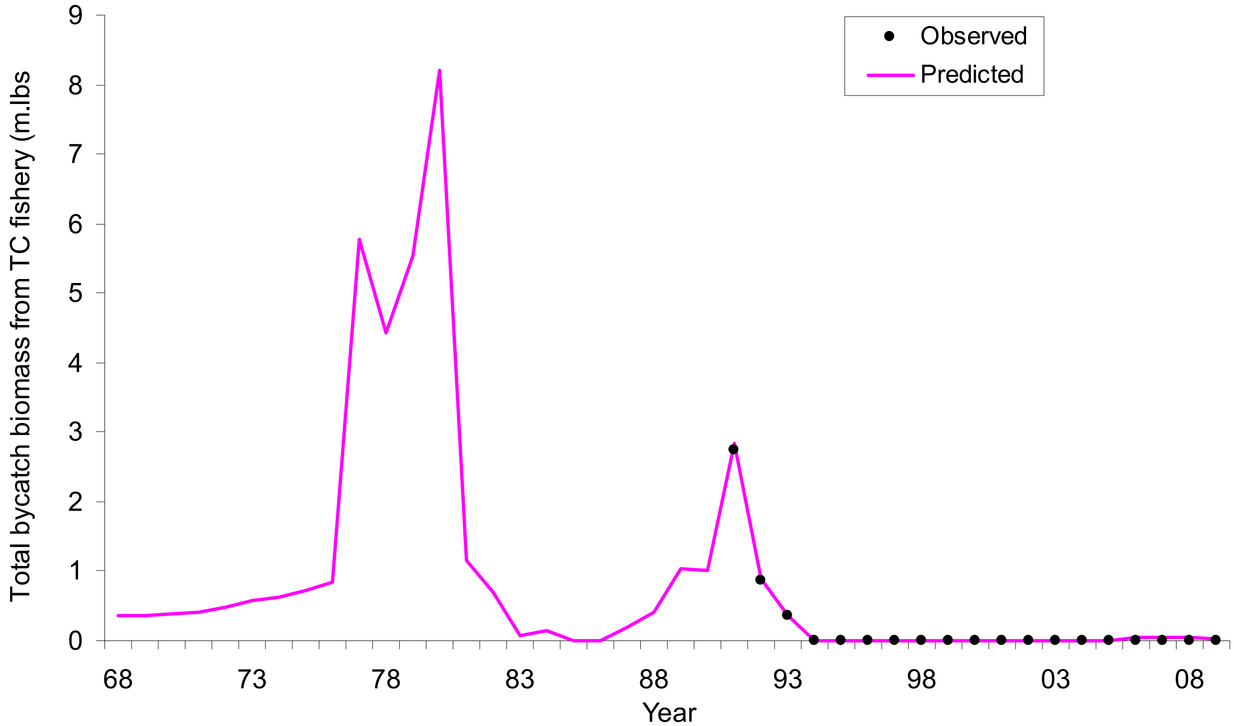
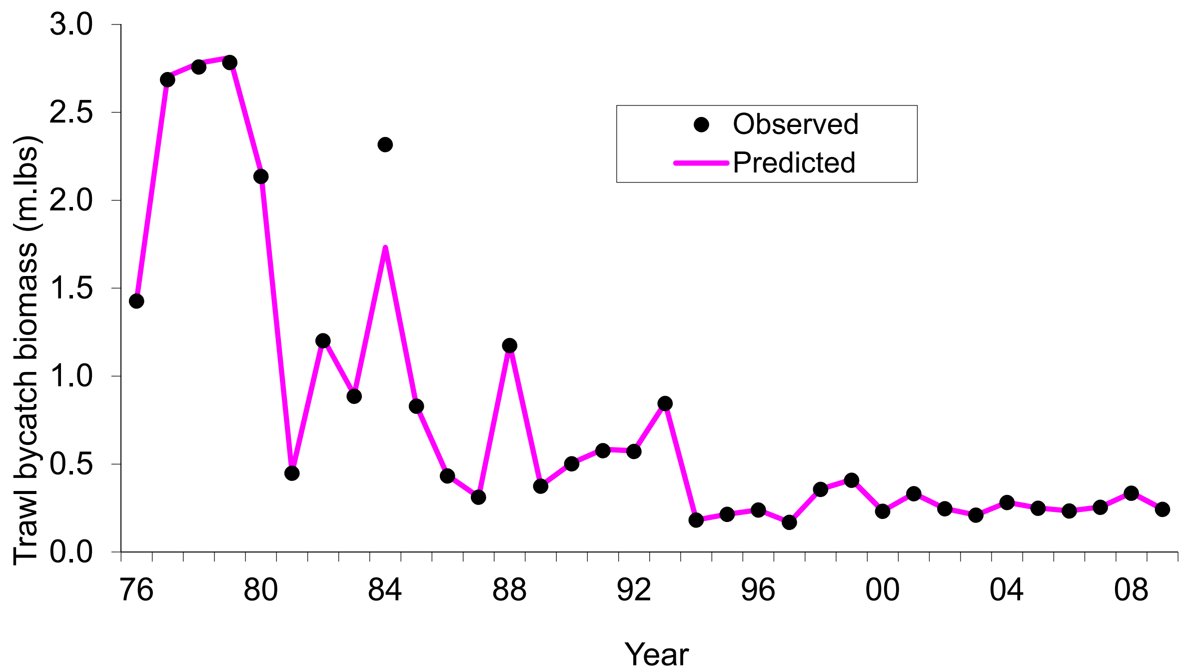


Figure 15b(0). Observed and predicted bycatch mortality biomass from trawl fisheries and Tanner crab fishery under scenario (0). Mortality biomass is equal to caught biomass times a handling mortality rate. Trawl handling mortality rate is 0.8, and Tanner crab pot handling mortality is 0.25.



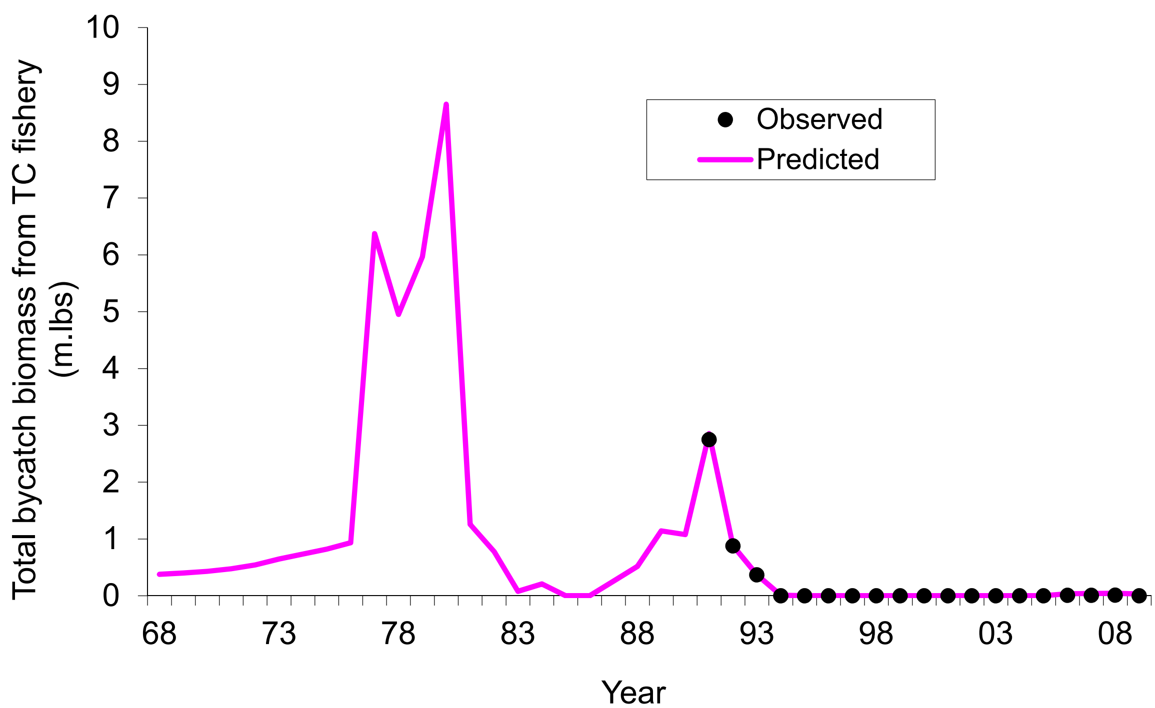


Figure 15b(1). Observed and predicted bycatch mortality biomass from trawl fisheries and Tanner crab fishery under scenario (1). Mortality biomass is equal to caught biomass times a handling mortality rate. Trawl handling mortality rate is 0.8, and Tanner crab pot handling mortality is 0.25.

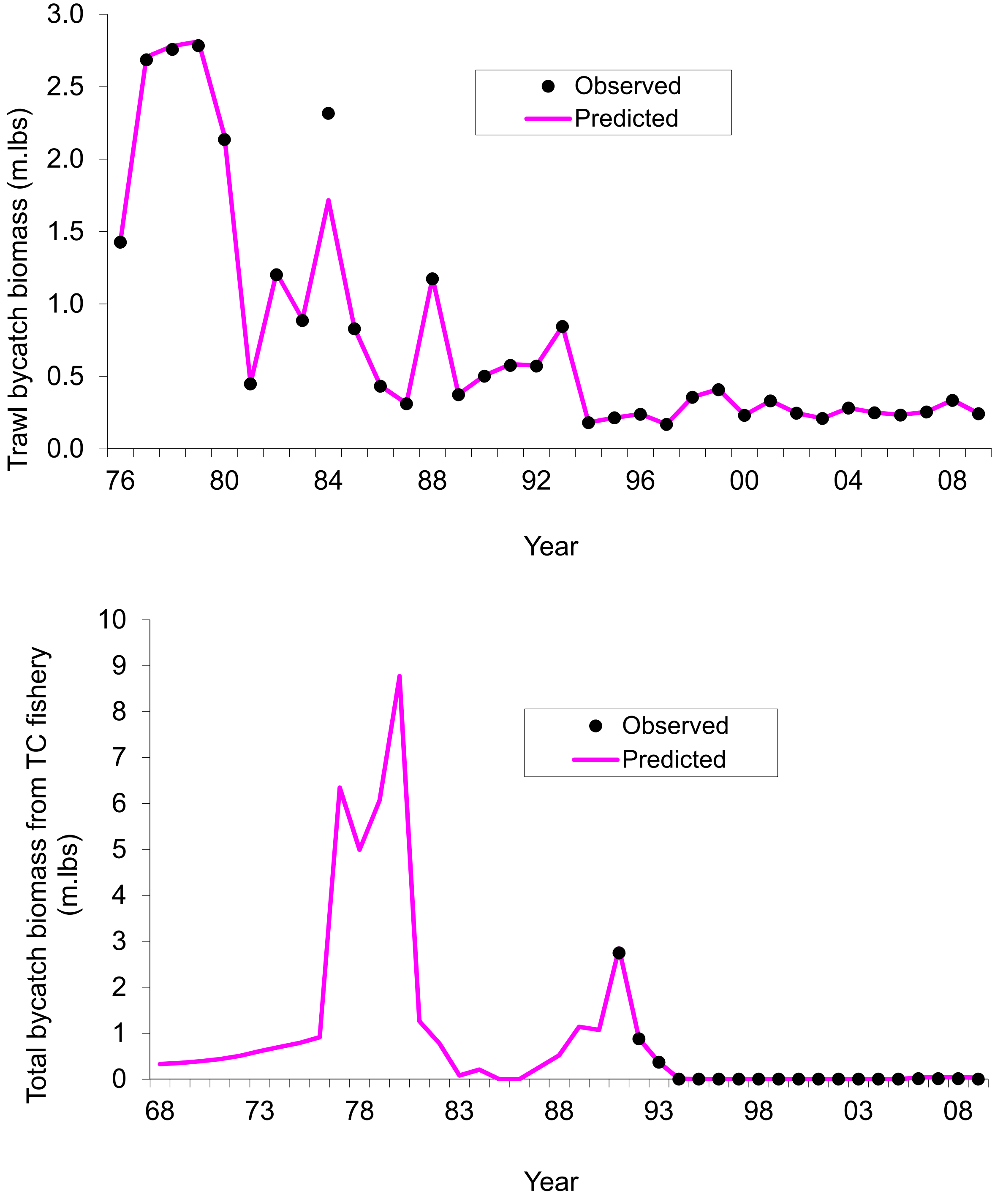
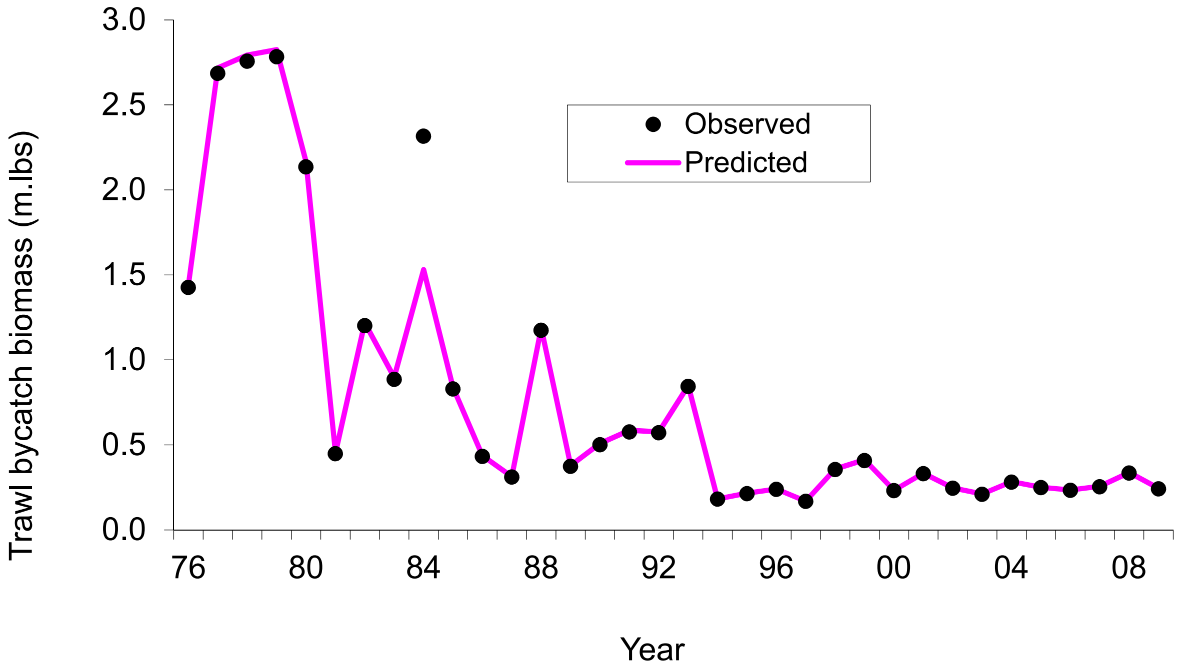


Figure 15b(2). Observed and predicted bycatch mortality biomass from trawl fisheries and Tanner crab fishery under scenario (2). Mortality biomass is equal to caught biomass times a handling mortality rate. Trawl handling mortality rate is 0.8, and Tanner crab pot handling mortality is 0.25.



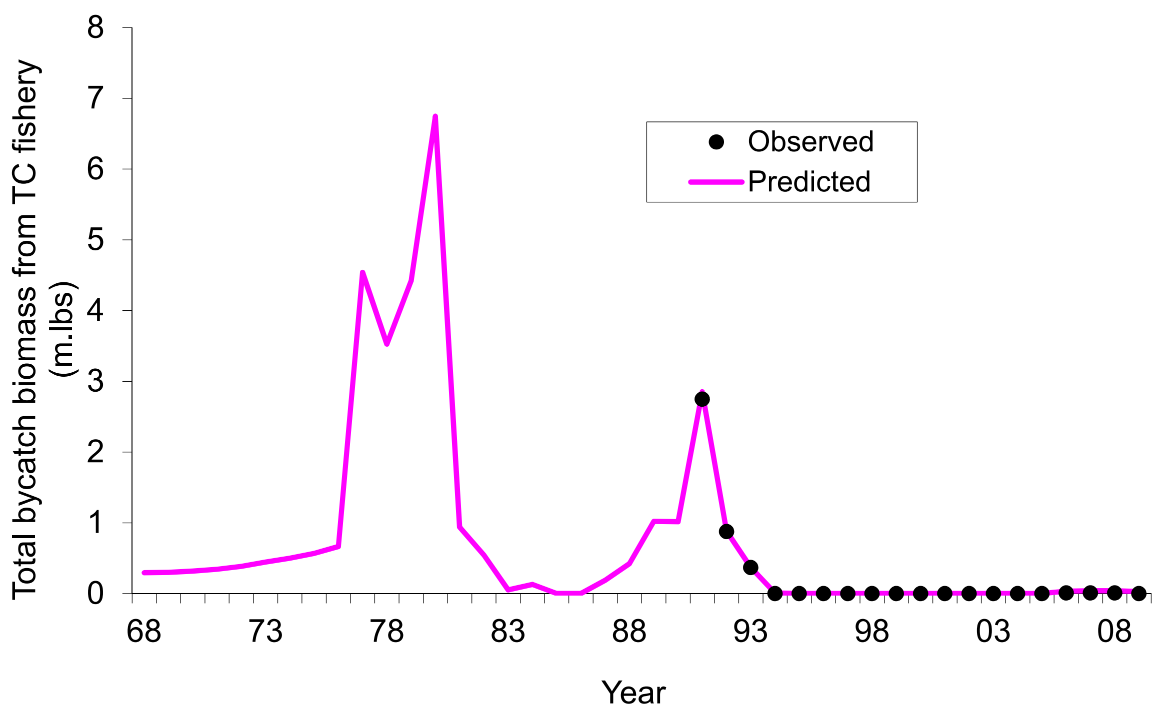
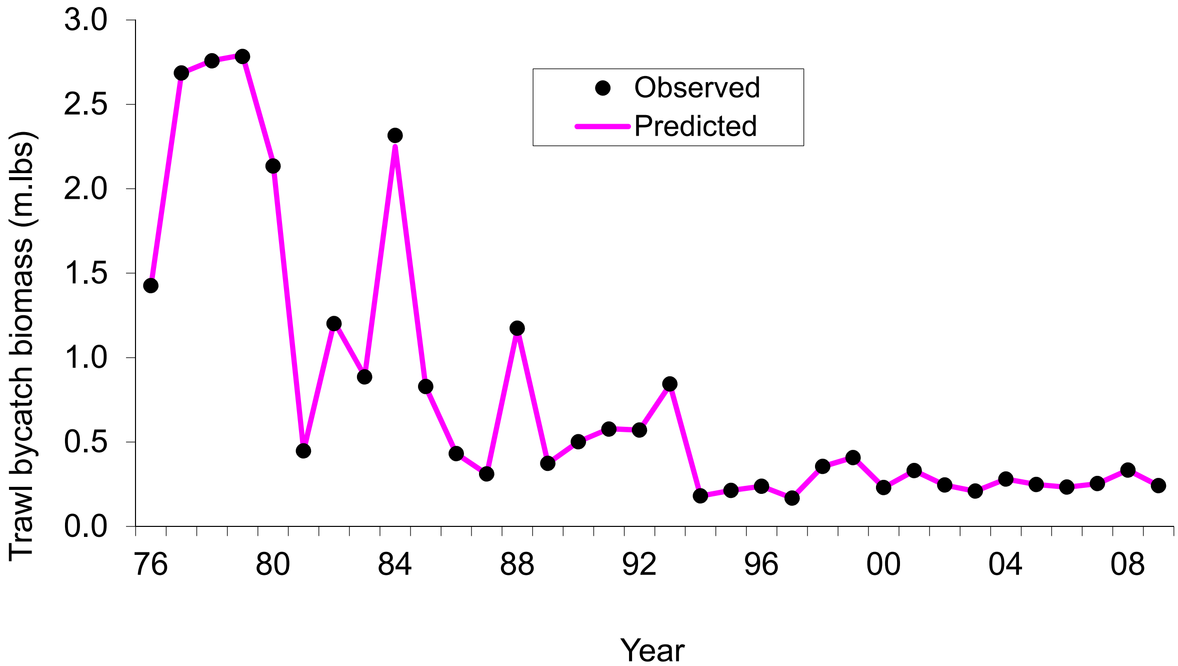


Figure 15b(3). Observed and predicted bycatch mortality biomass from trawl fisheries and Tanner crab fishery under scenario (3). Mortality biomass is equal to caught biomass times a handling mortality rate. Trawl handling mortality rate is 0.8, and Tanner crab pot handling mortality is 0.25.



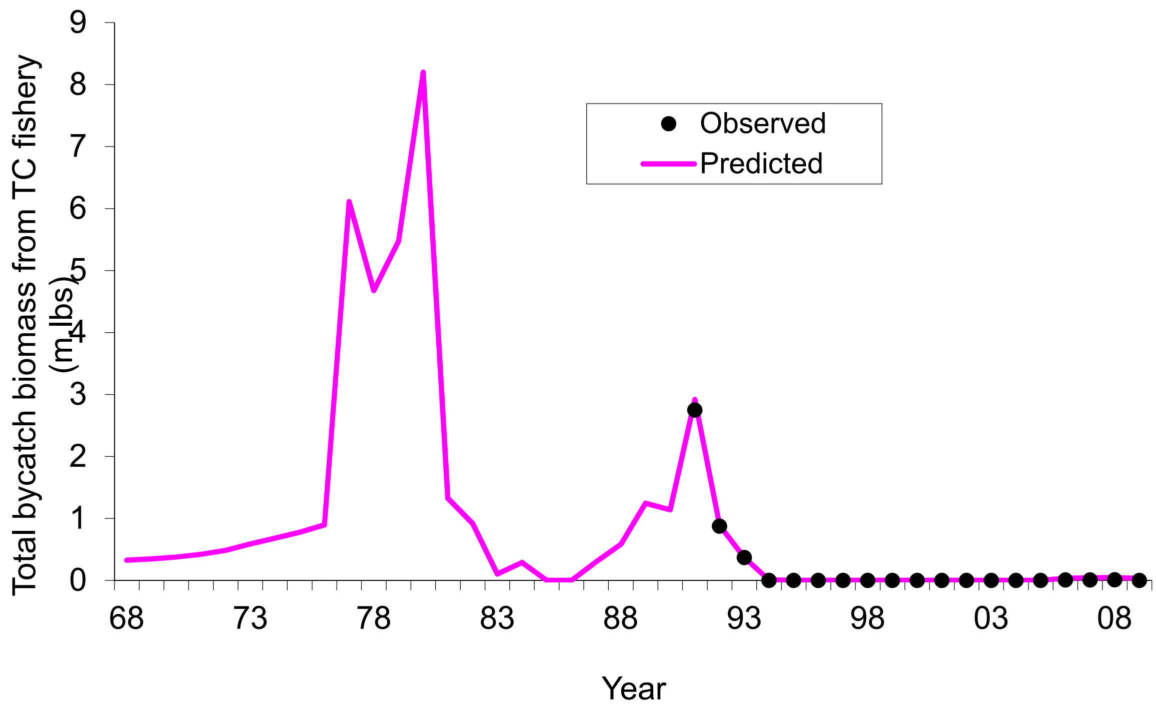
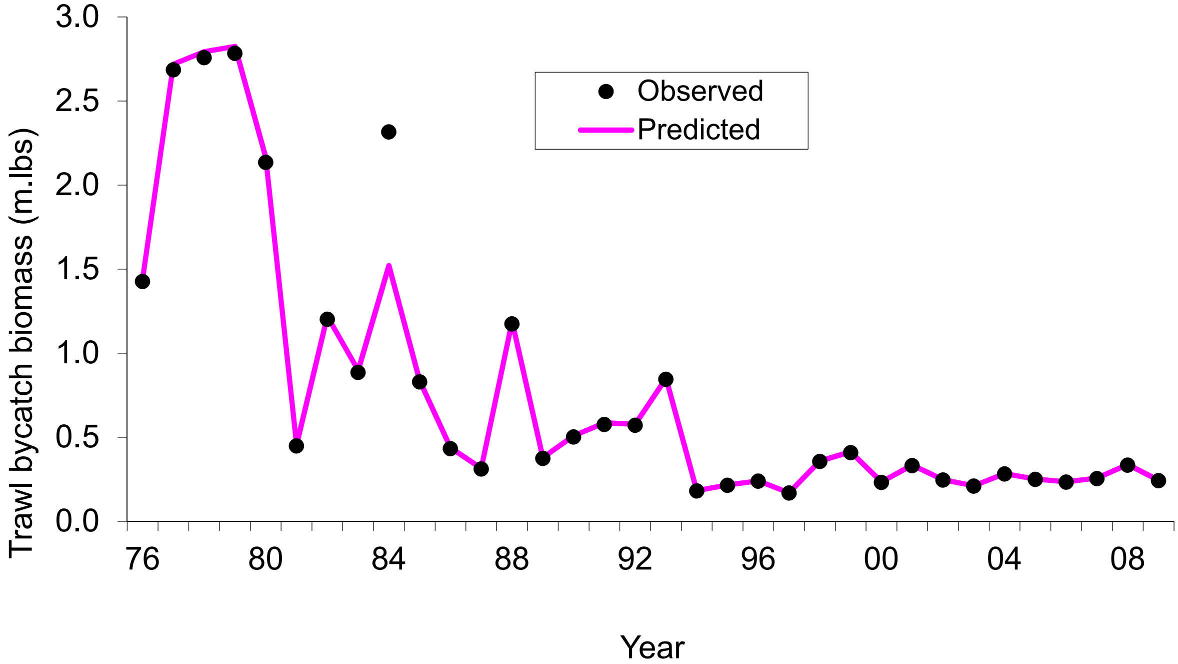


Figure 15b(4). Observed and predicted bycatch mortality biomass from trawl fisheries and Tanner crab fishery under scenario (4). Mortality biomass is equal to caught biomass times a handling mortality rate. Trawl handling mortality rate is 0.8, and Tanner crab pot handling mortality is 0.25.



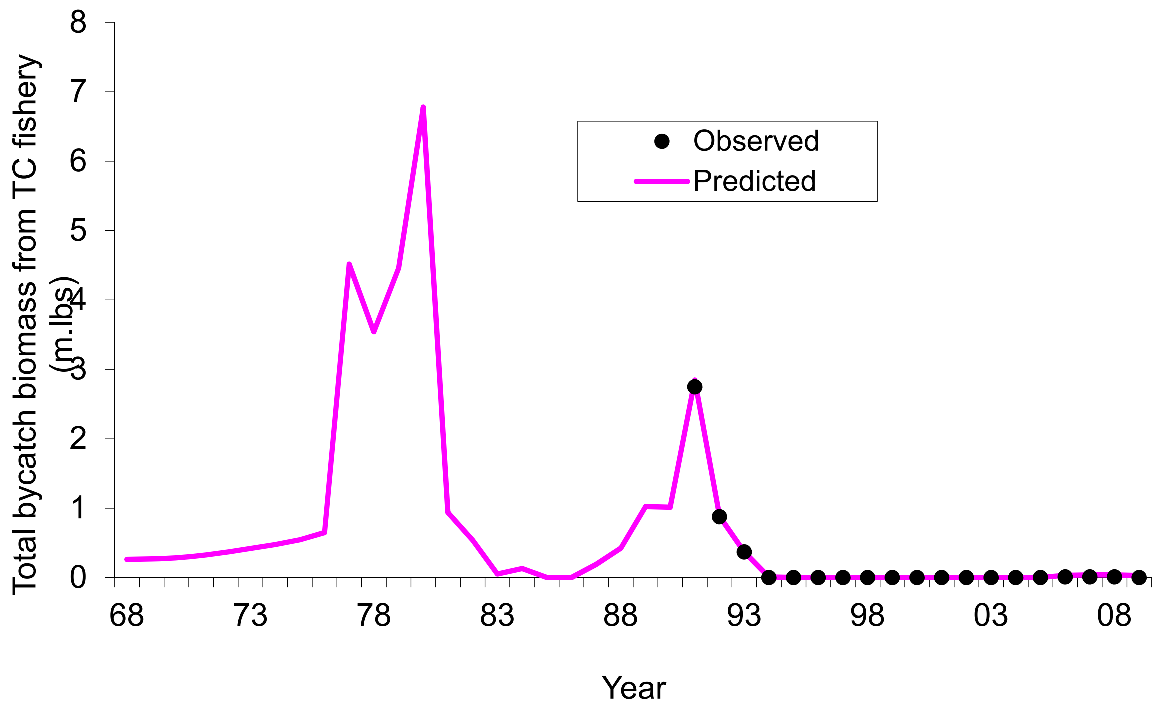
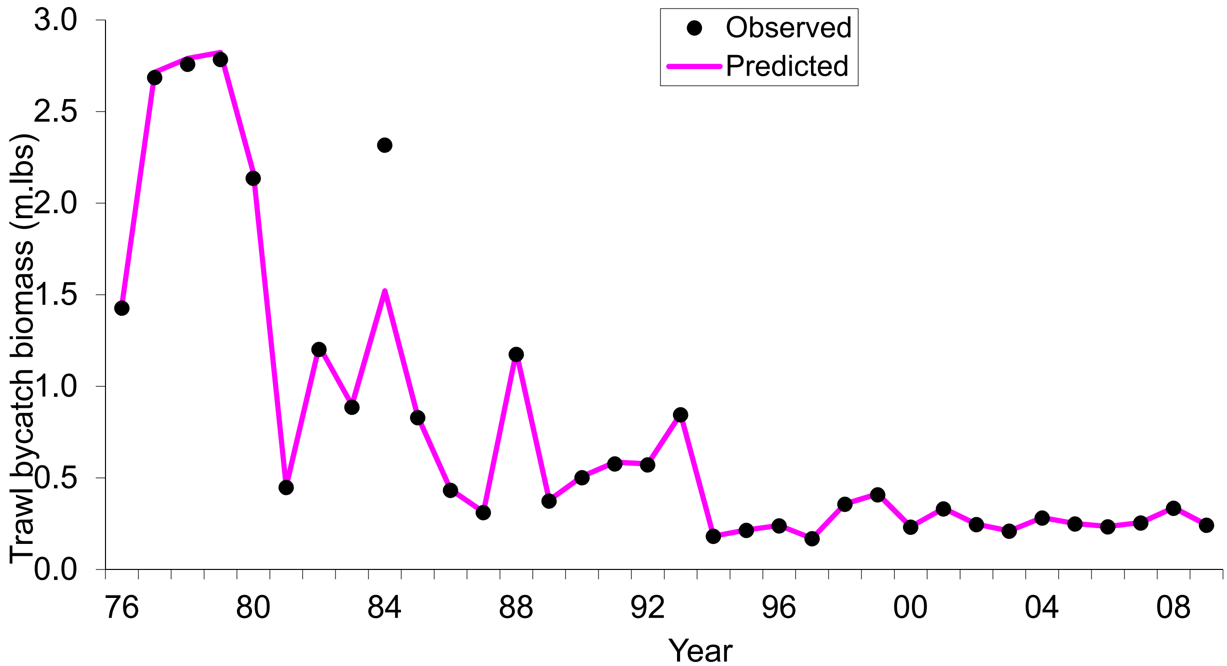


Figure 15b(5). Observed and predicted bycatch mortality biomass from trawl fisheries and Tanner crab fishery under scenario (5). Mortality biomass is equal to caught biomass times a handling mortality rate. Trawl handling mortality rate is 0.8, and Tanner crab pot handling mortality is 0.25.



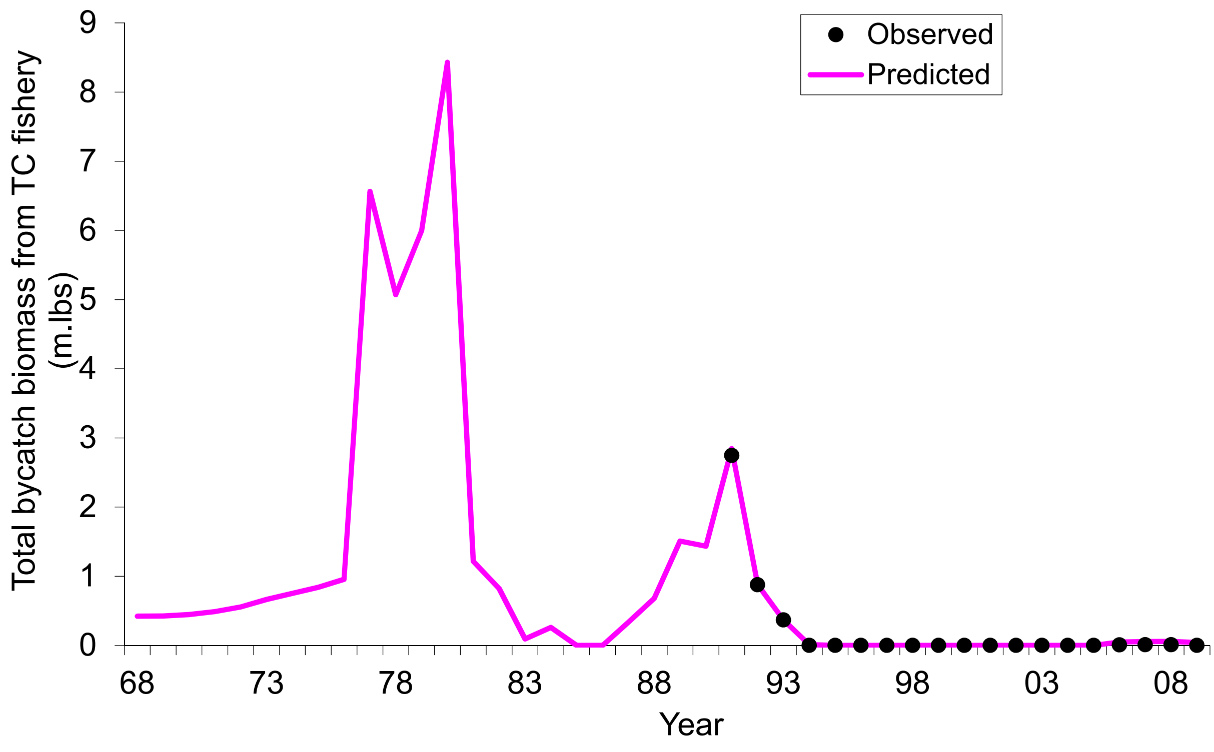
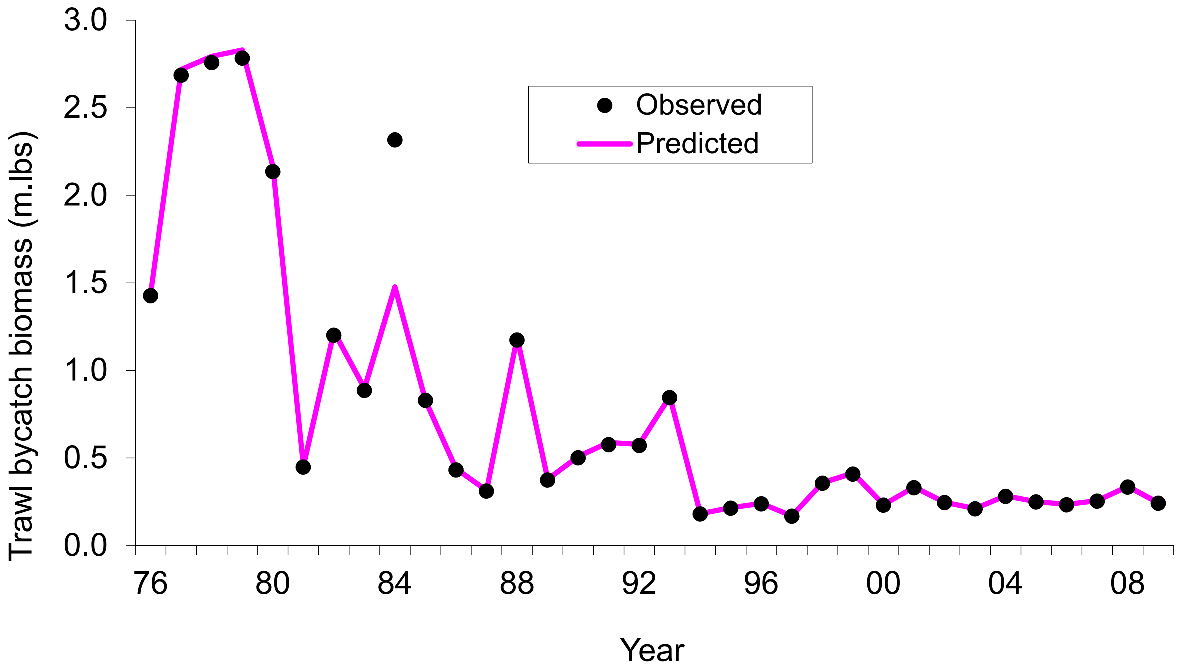


Figure 15b(6). Observed and predicted bycatch mortality biomass from trawl fisheries and Tanner crab fishery under scenario (6). Mortality biomass is equal to caught biomass times a handling mortality rate. Trawl handling mortality rate is 0.8, and Tanner crab pot handling mortality is 0.25.



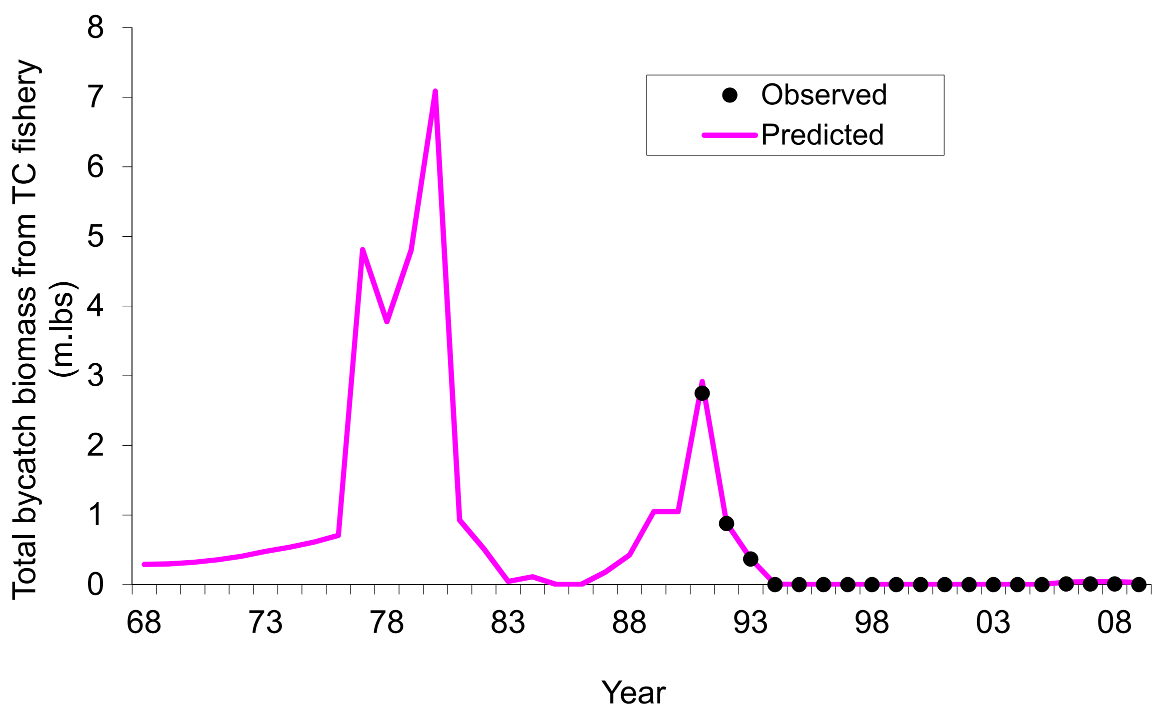


Figure 15b(7). Observed and predicted bycatch mortality biomass from trawl fisheries and Tanner crab fishery under scenario (7). Mortality biomass is equal to caught biomass times a handling mortality rate. Trawl handling mortality rate is 0.8, and Tanner crab pot handling mortality is 0.25.

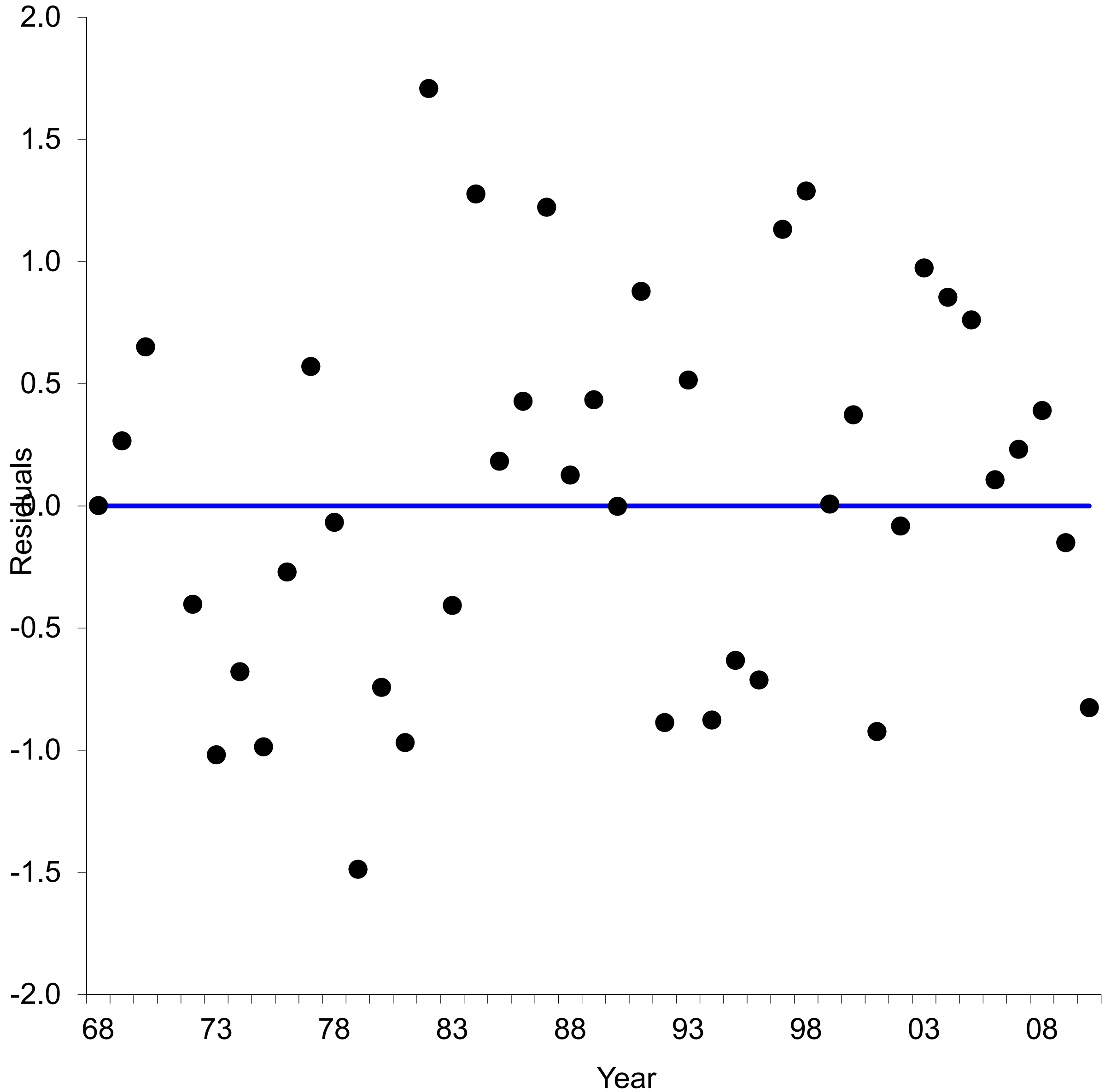


Figure 16(0). Standardized residuals of total survey biomass under scenario 0. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

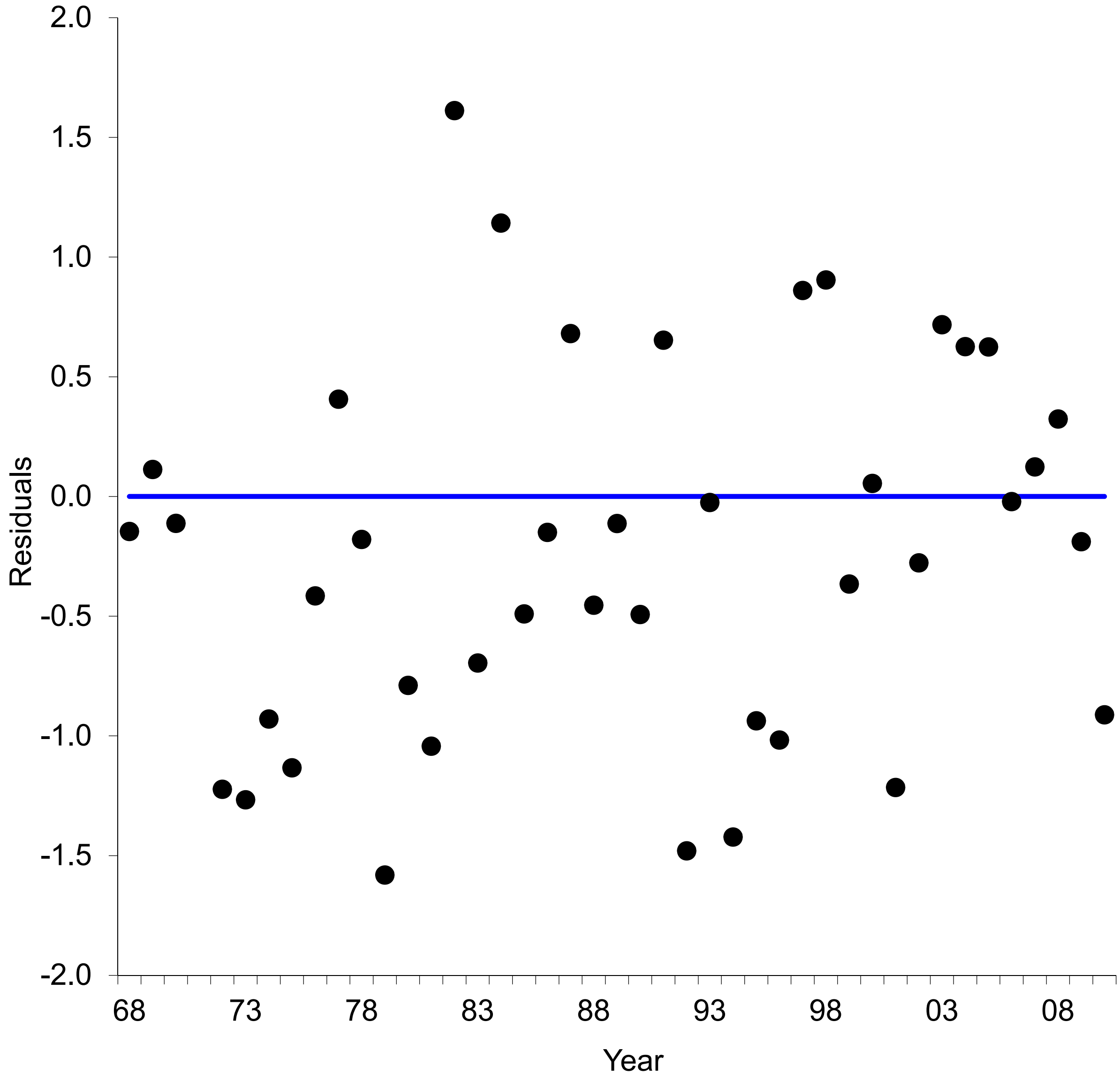


Figure 16(1). Standardized residuals of total survey biomass under scenario 1. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

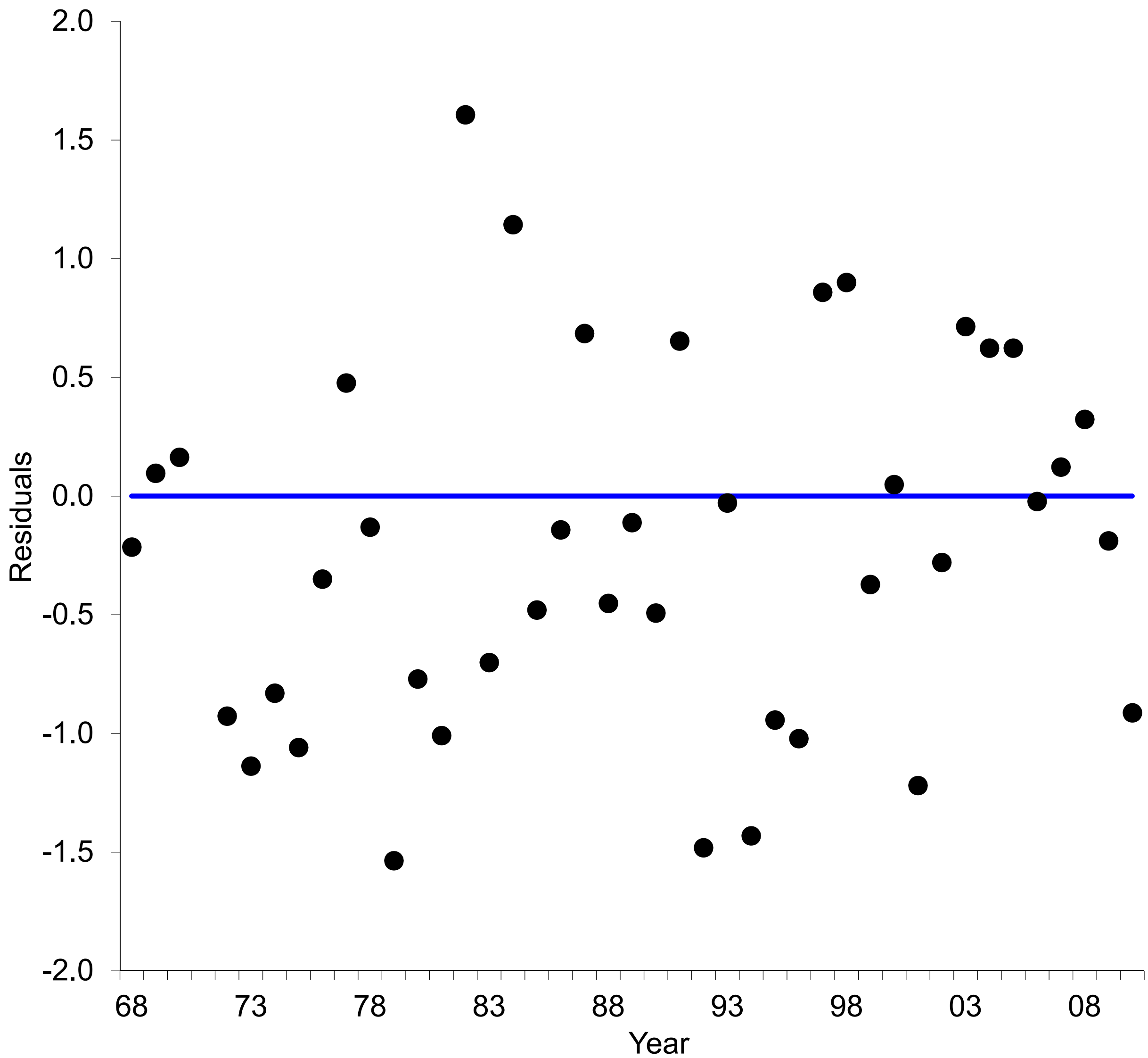


Figure 16(1a). Standardized residuals of total survey biomass under scenario 1a. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

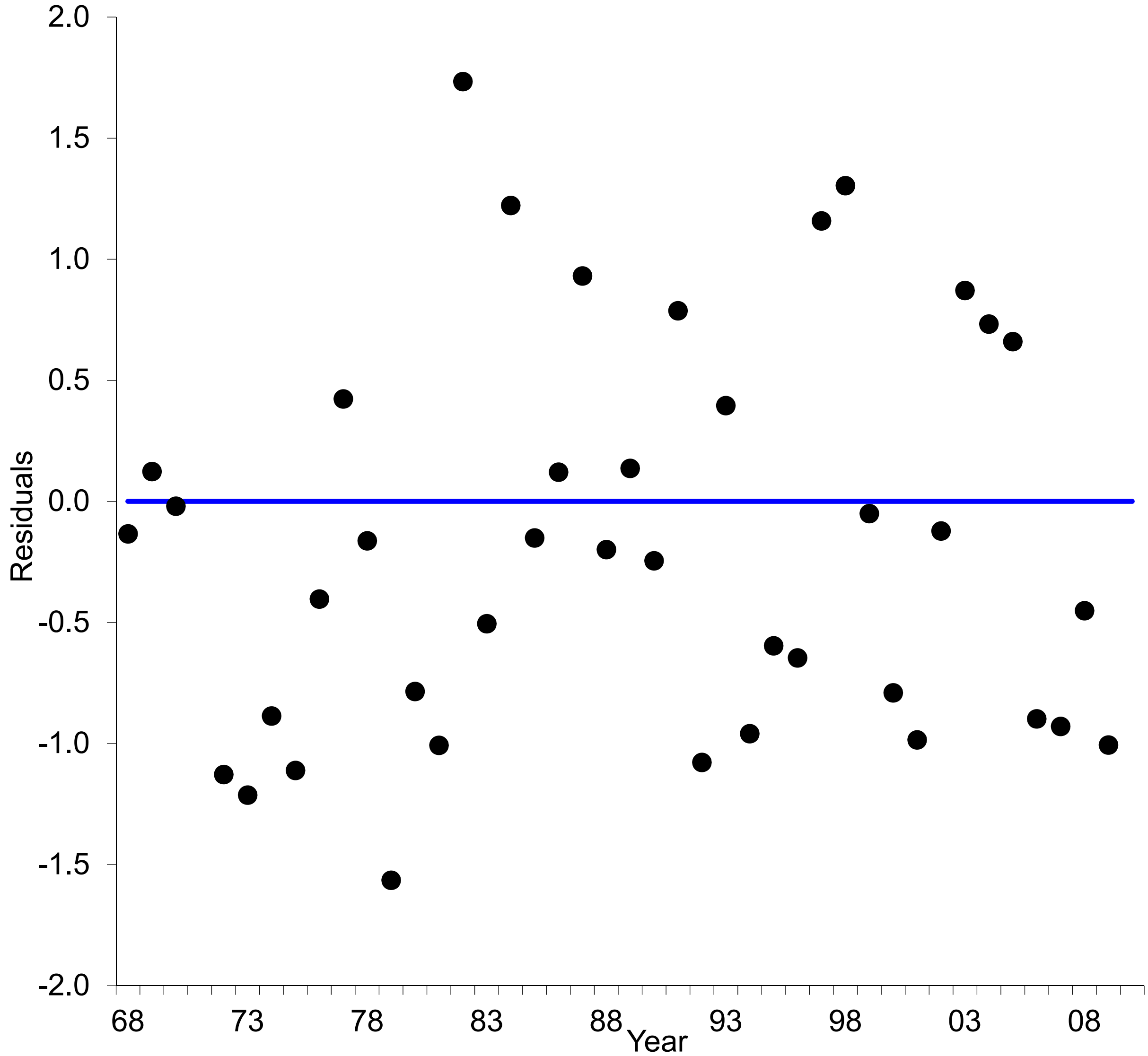


Figure 16(1b). Standardized residuals of total survey biomass under scenario 1b. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

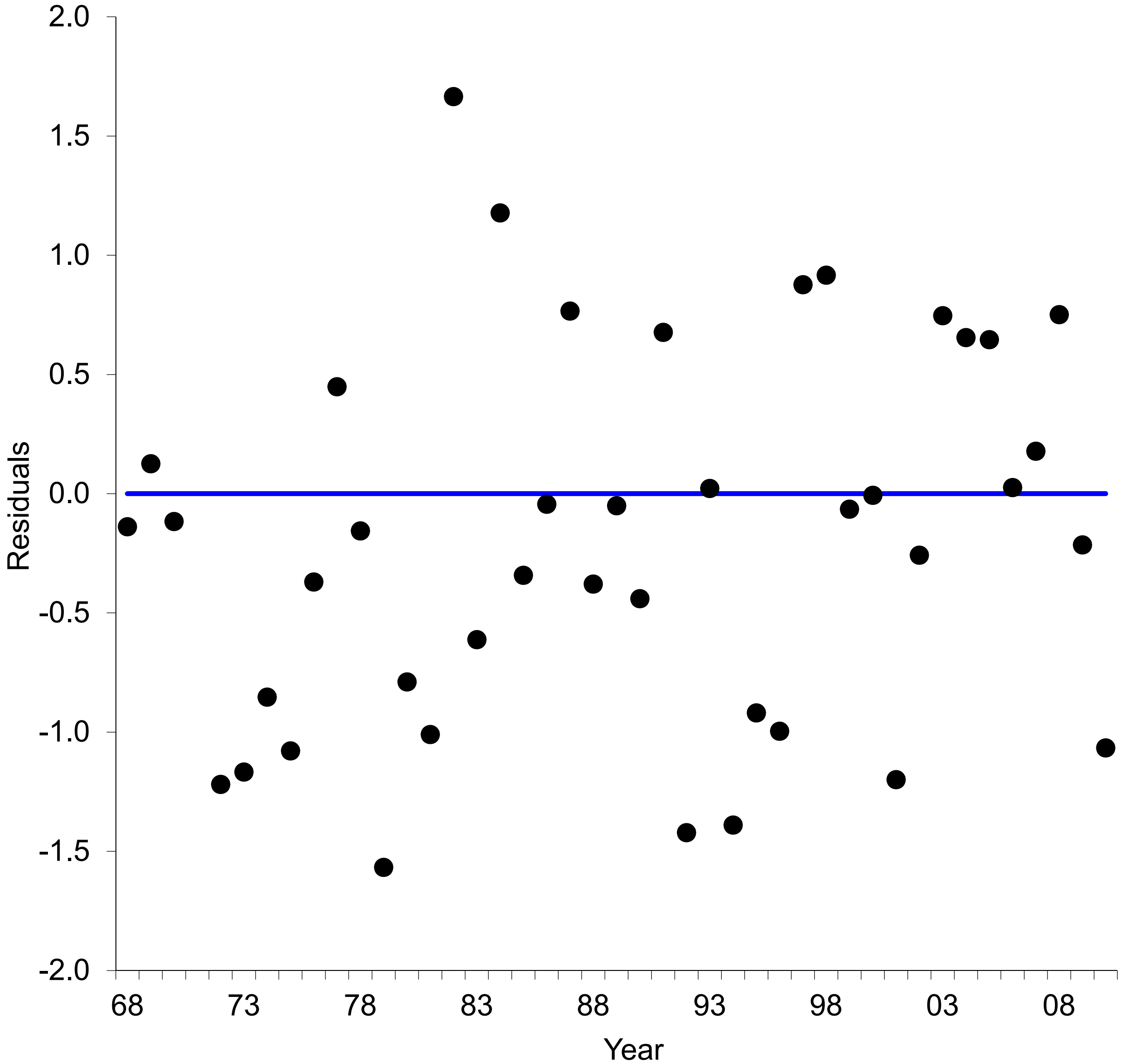


Figure 16(1c). Standardized residuals of total survey biomass under scenario 1c. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

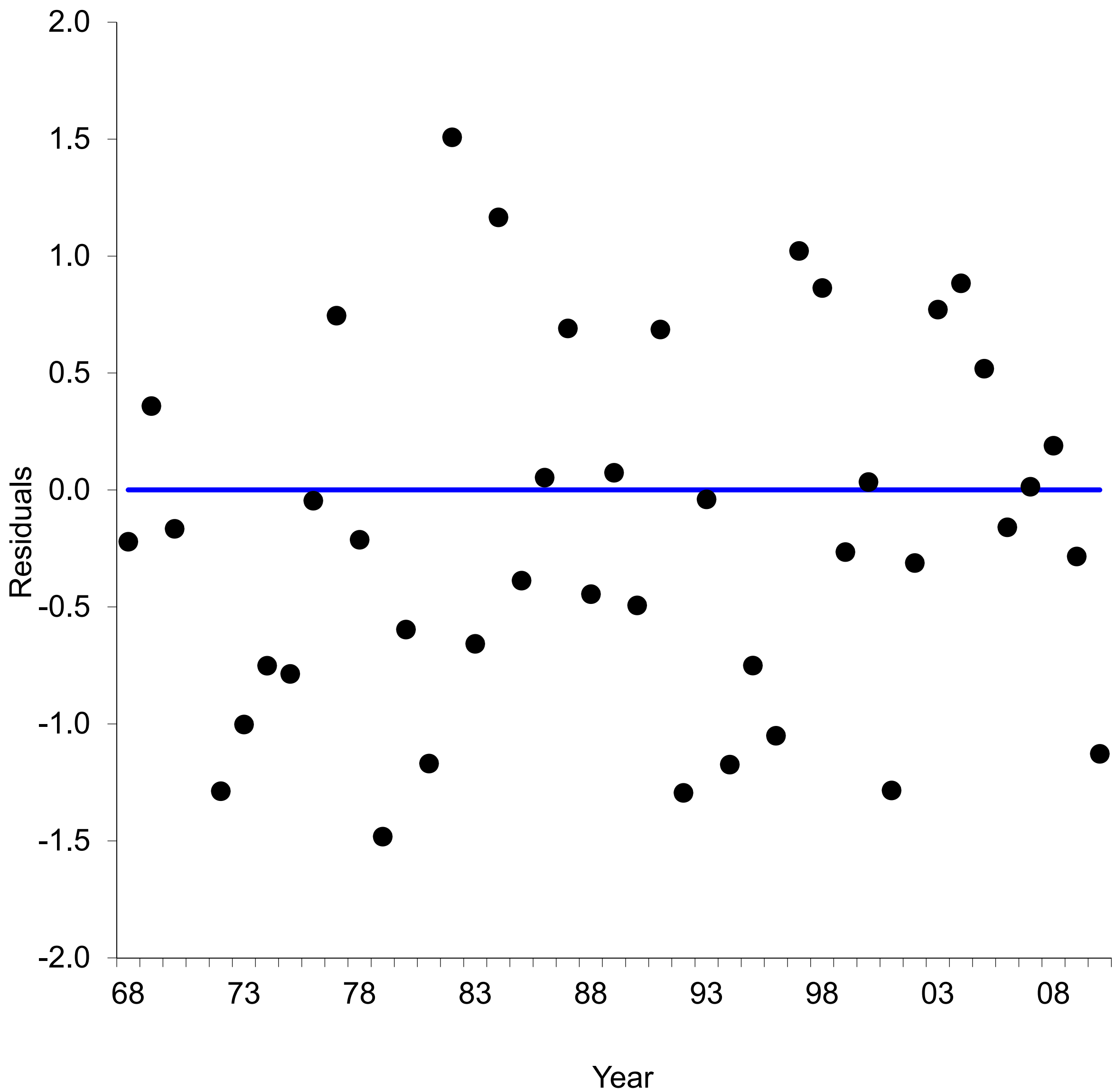


Figure 16(2). Standardized residuals of total survey biomass under scenario 2. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

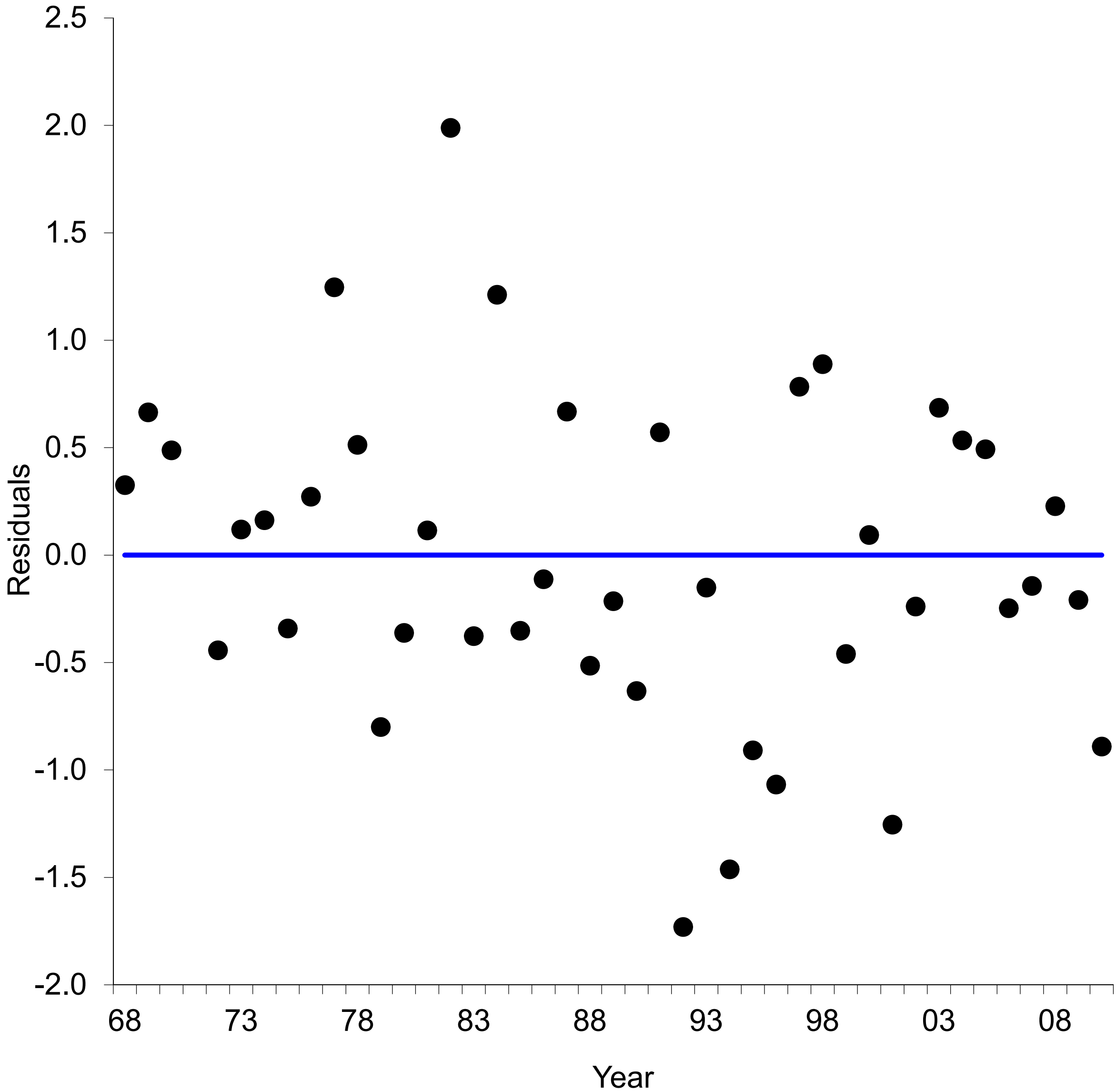


Figure 16(3). Standardized residuals of total survey biomass under scenario 3. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

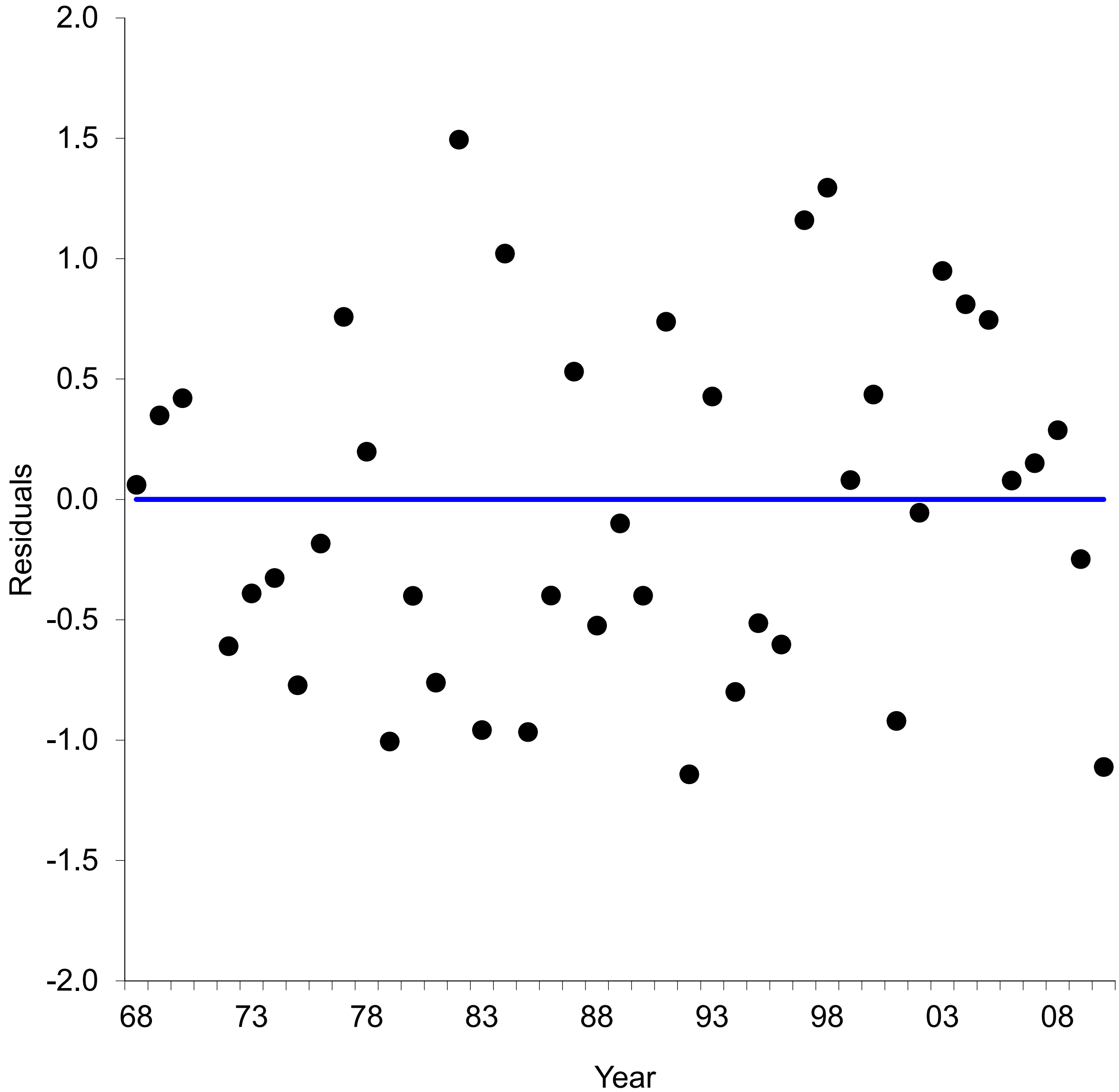


Figure 16(4). Standardized residuals of total survey biomass under scenario 4. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

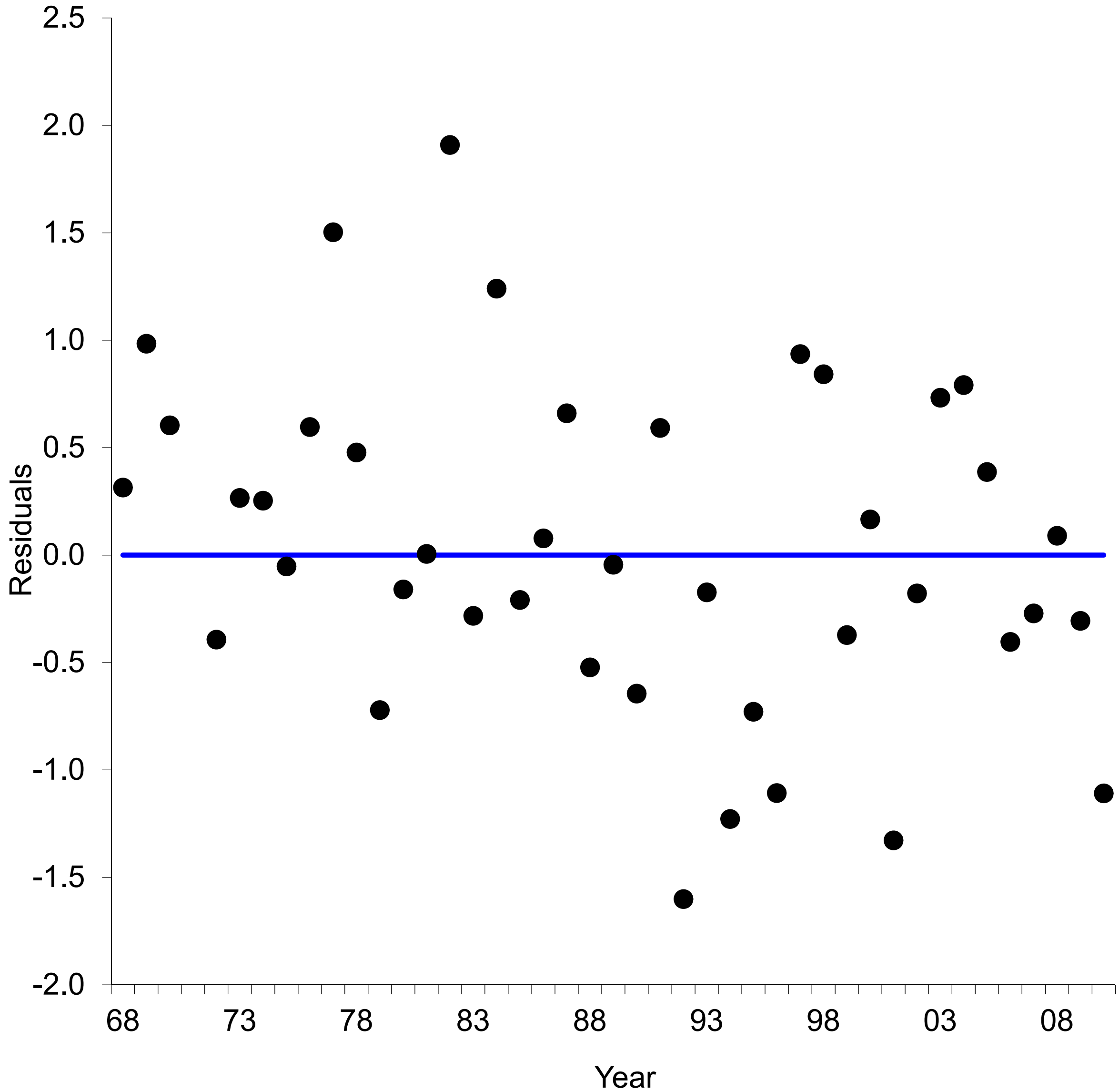


Figure 16(5). Standardized residuals of total survey biomass under scenario 5. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

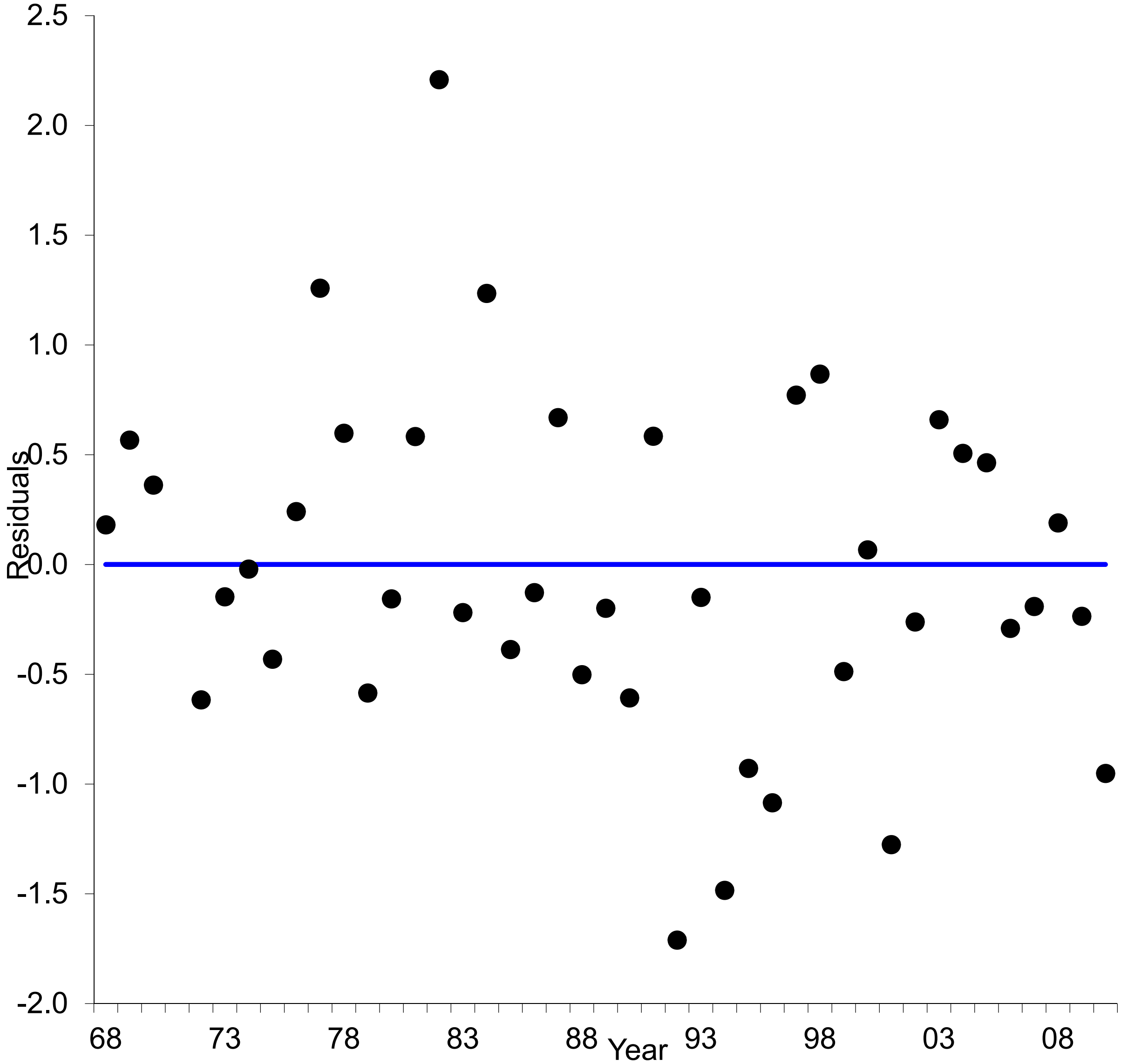


Figure 16(6). Standardized residuals of total survey biomass under scenario 6. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

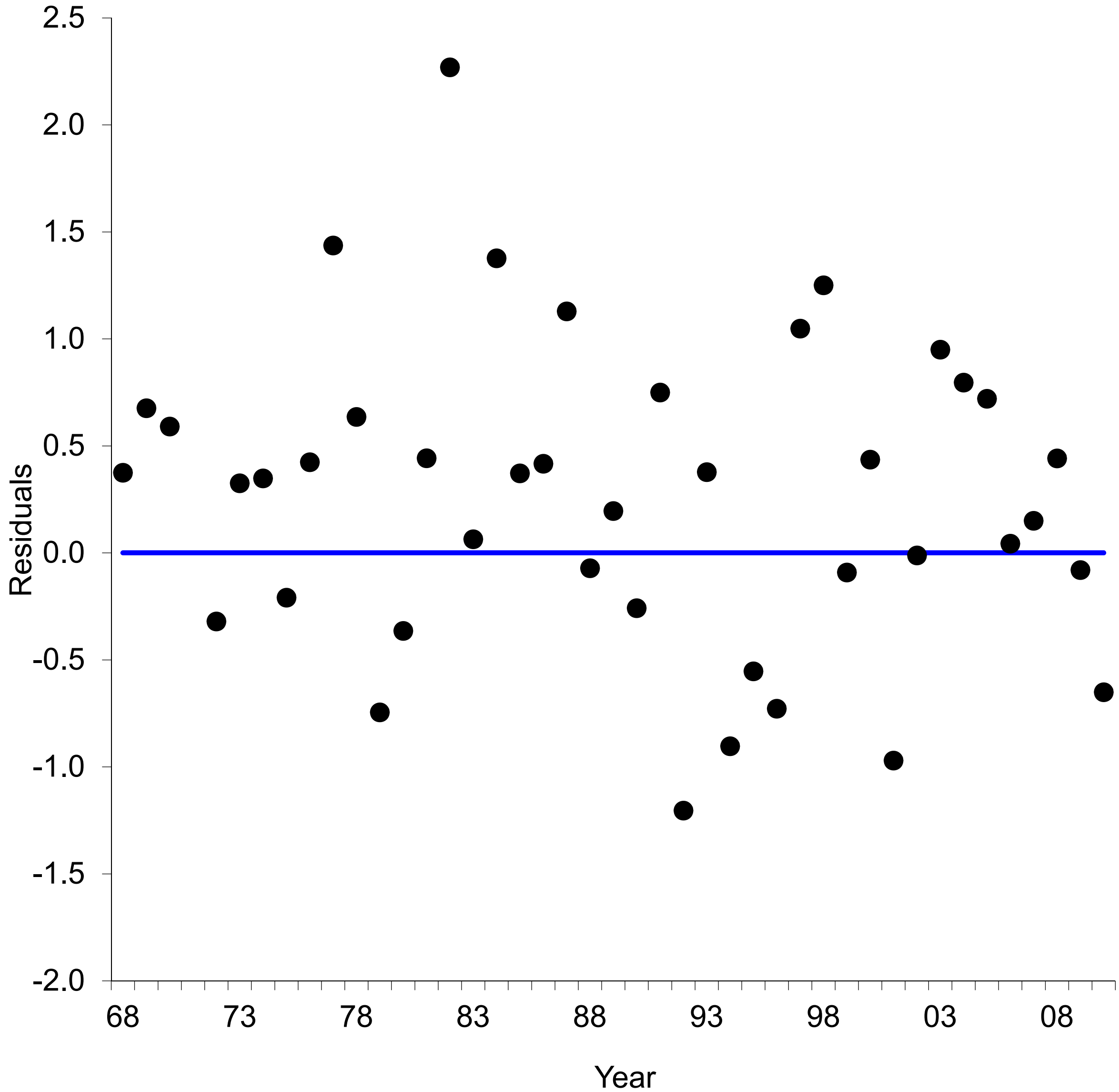


Figure 16(7). Standardized residuals of total survey biomass under scenario 7. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

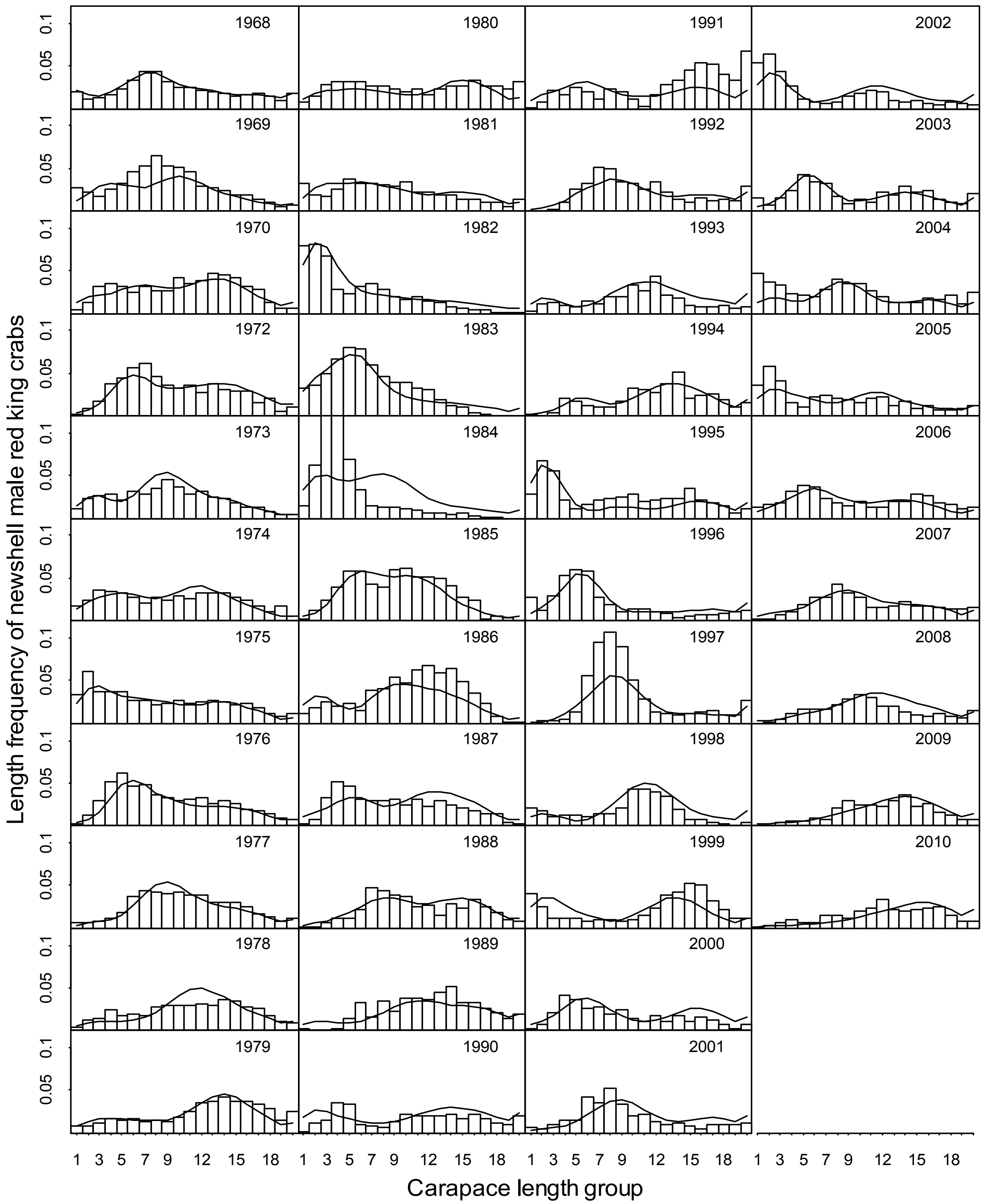


Figure 17(0). Comparison of area-swept and model estimated survey length frequencies of Bristol Bay all-shell (before 1986) and newshell (1986-2010) male red king crabs by year under scenario 0. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, and the first length group is 67.5 mm.

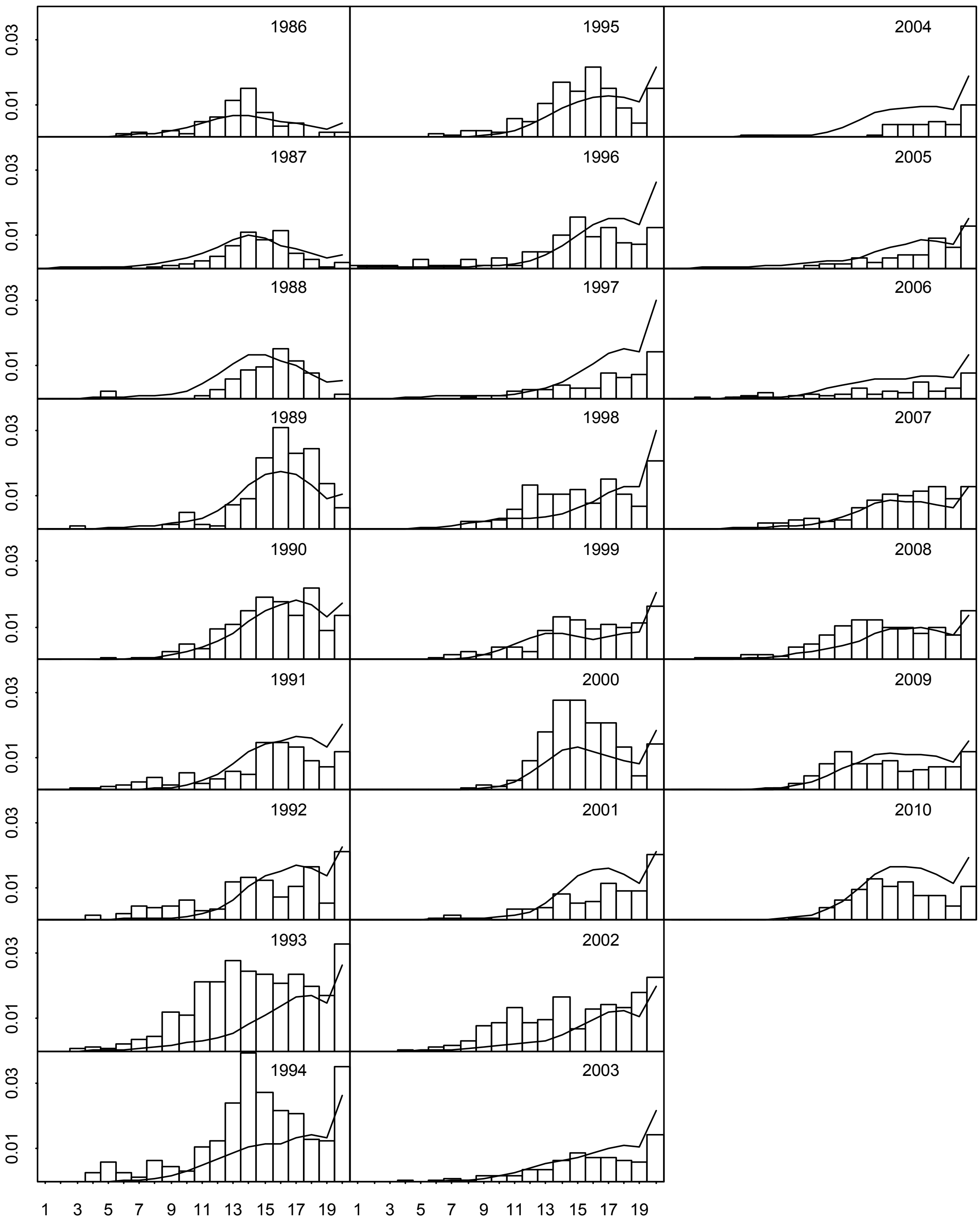


Figure 18(0). Comparison of area-swept and model estimated survey length frequencies of Bristol Bay oldshell male red king crabs by year under scenario 0. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the first length group is 67.5 mm.

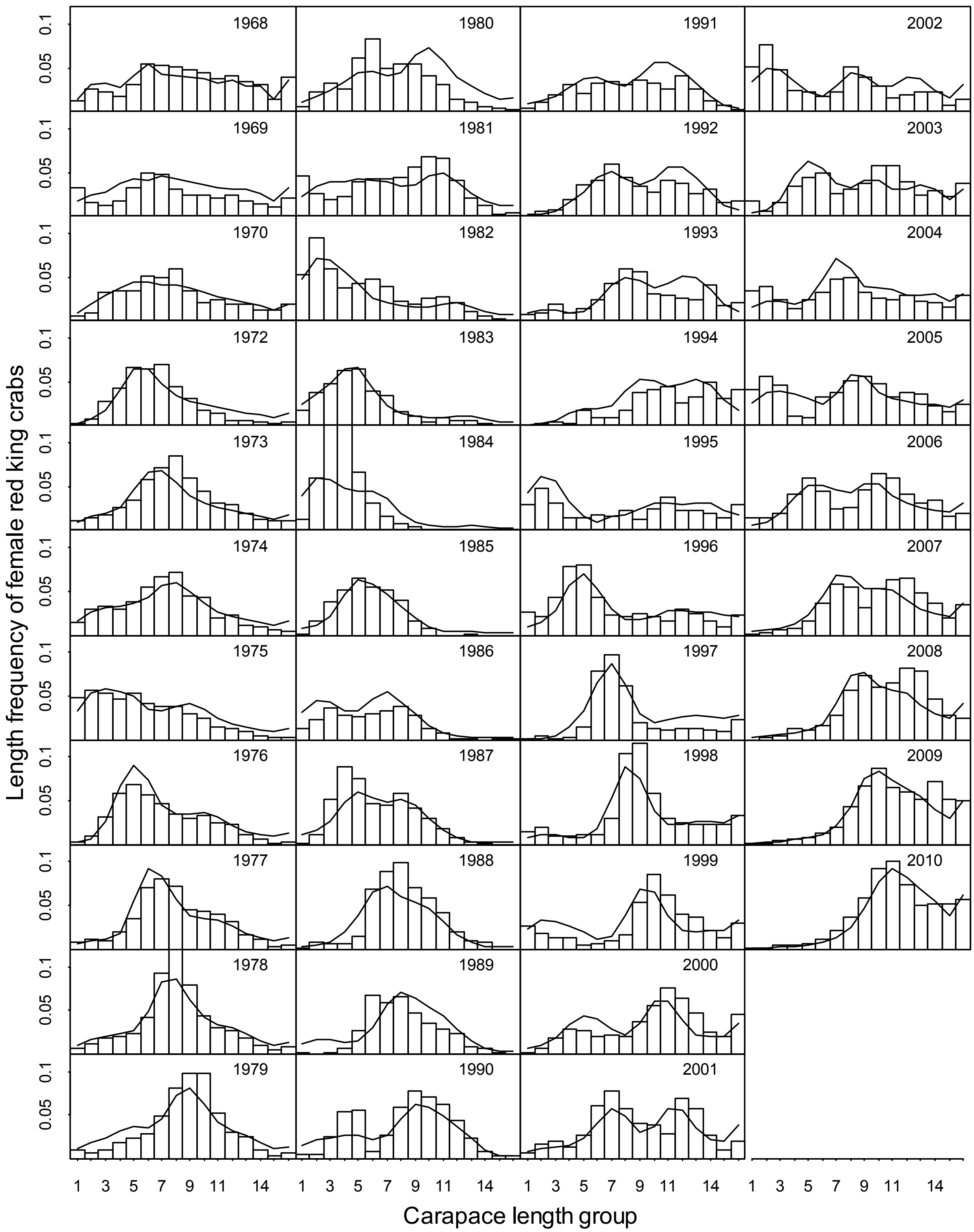


Figure 19(0). Comparison of area-swept and model estimated survey length frequencies of Bristol Bay female red king crabs by year under scenario 0. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the first length group is 67.5 mm.

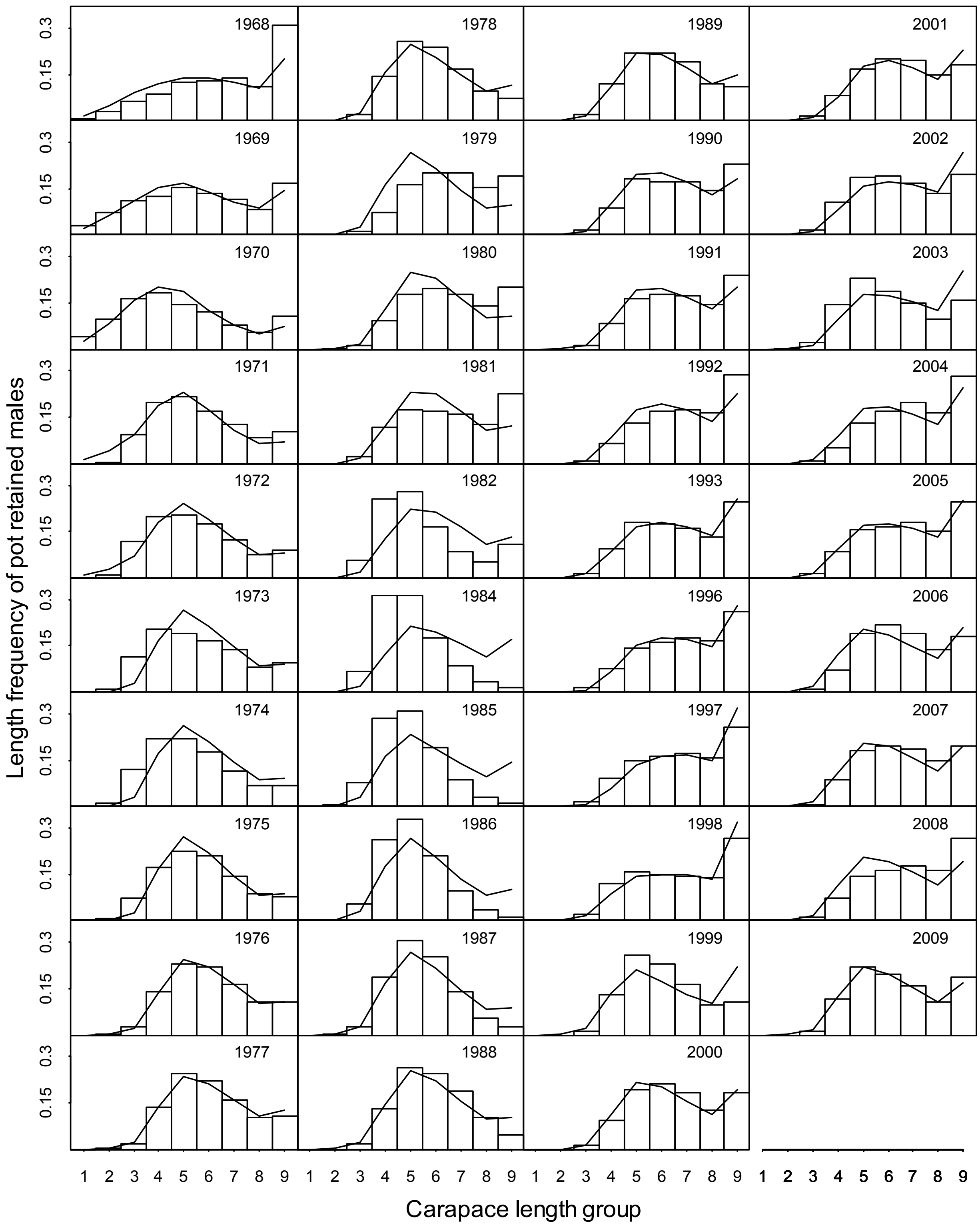


Figure 20(0). Comparison of observed and model estimated retained length frequencies of Bristol Bay male red king crabs by year in the directed pot fishery under scenario 0. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the first length group is 122.5 mm.

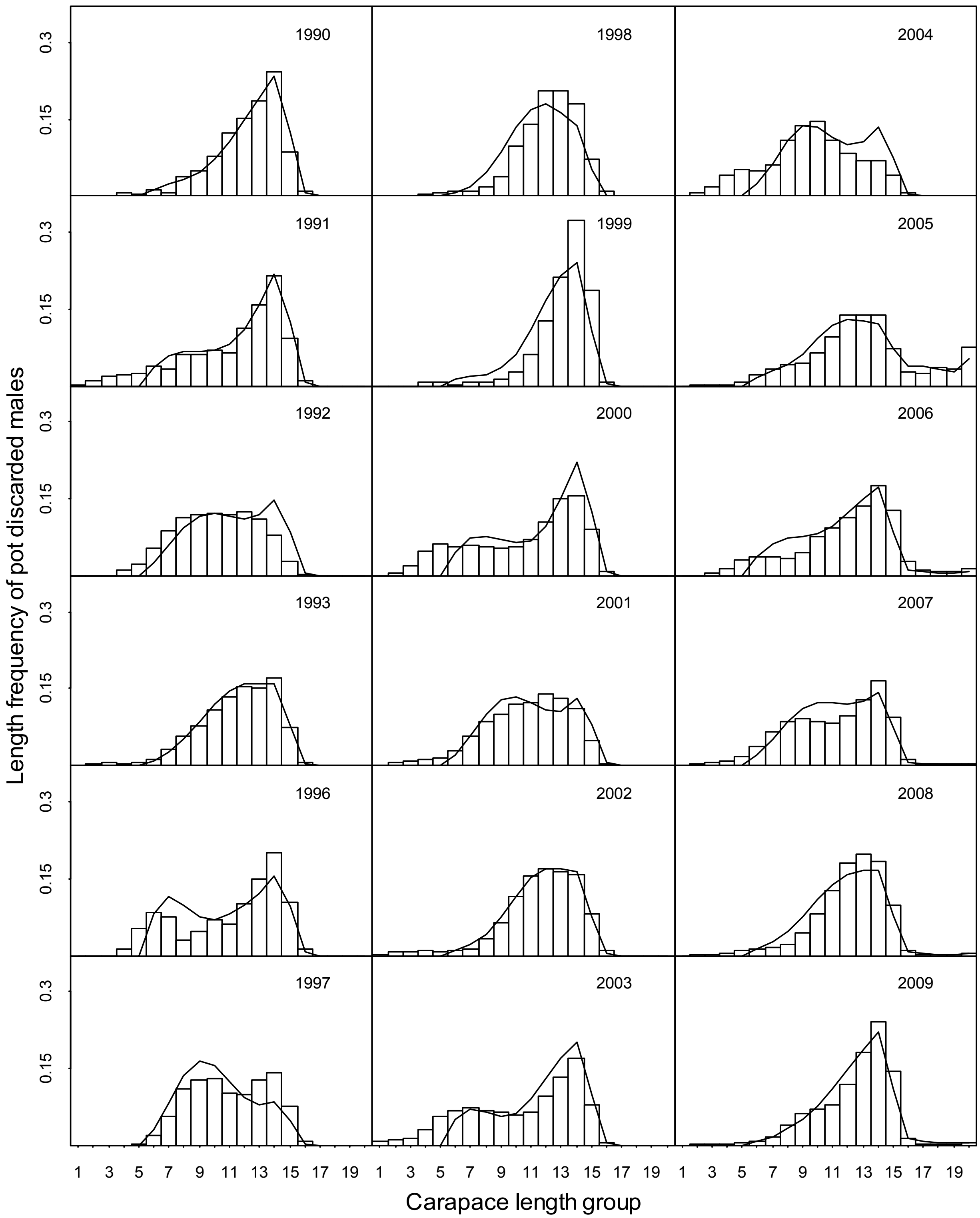


Figure 21(0). Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crabs by year in the directed pot fishery under scenario 0. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the first length group is 67.5 mm.

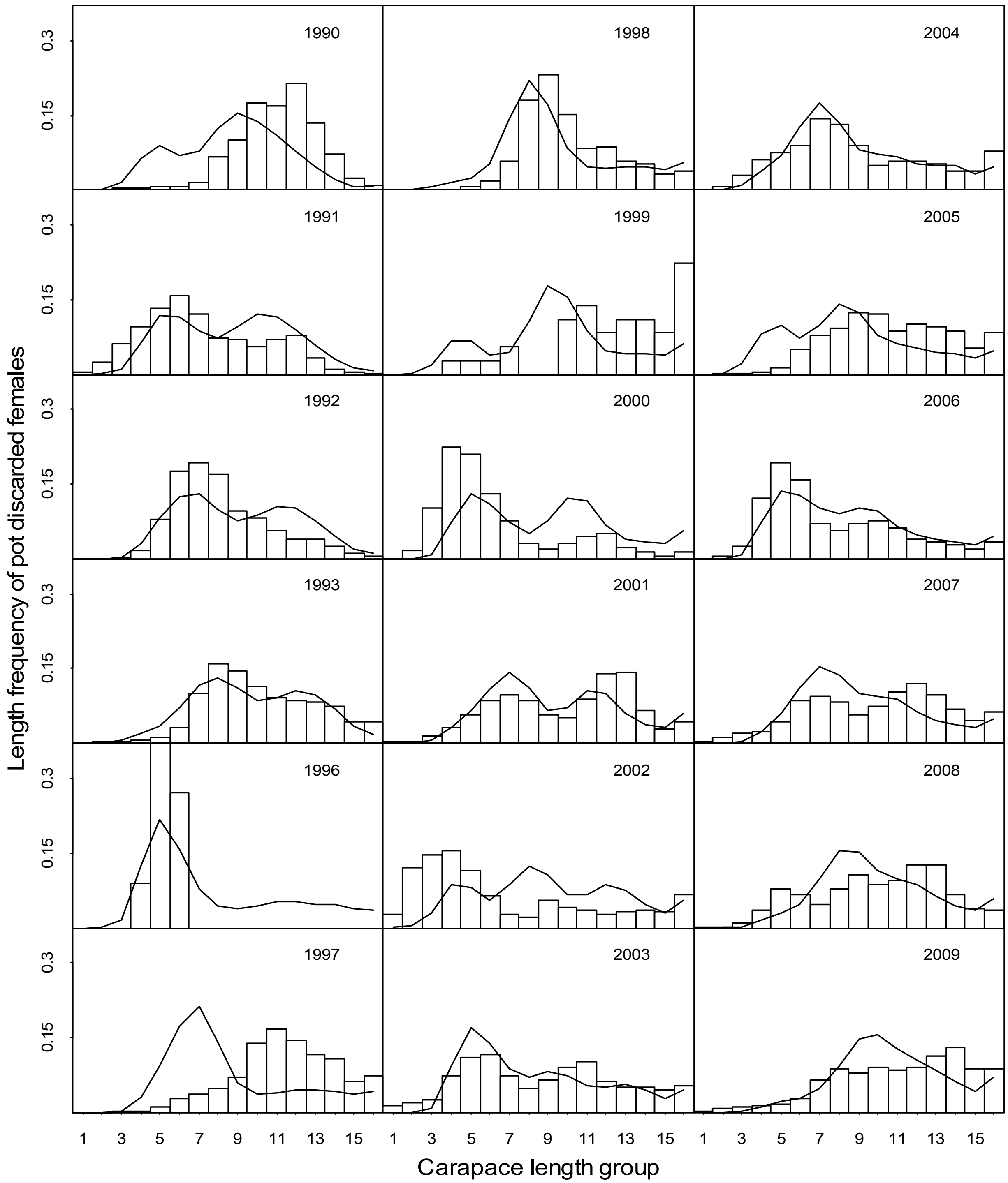


Figure 22(0). Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crabs by year in the directed pot fishery under scenario 0. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the first length group is 67.5 mm.

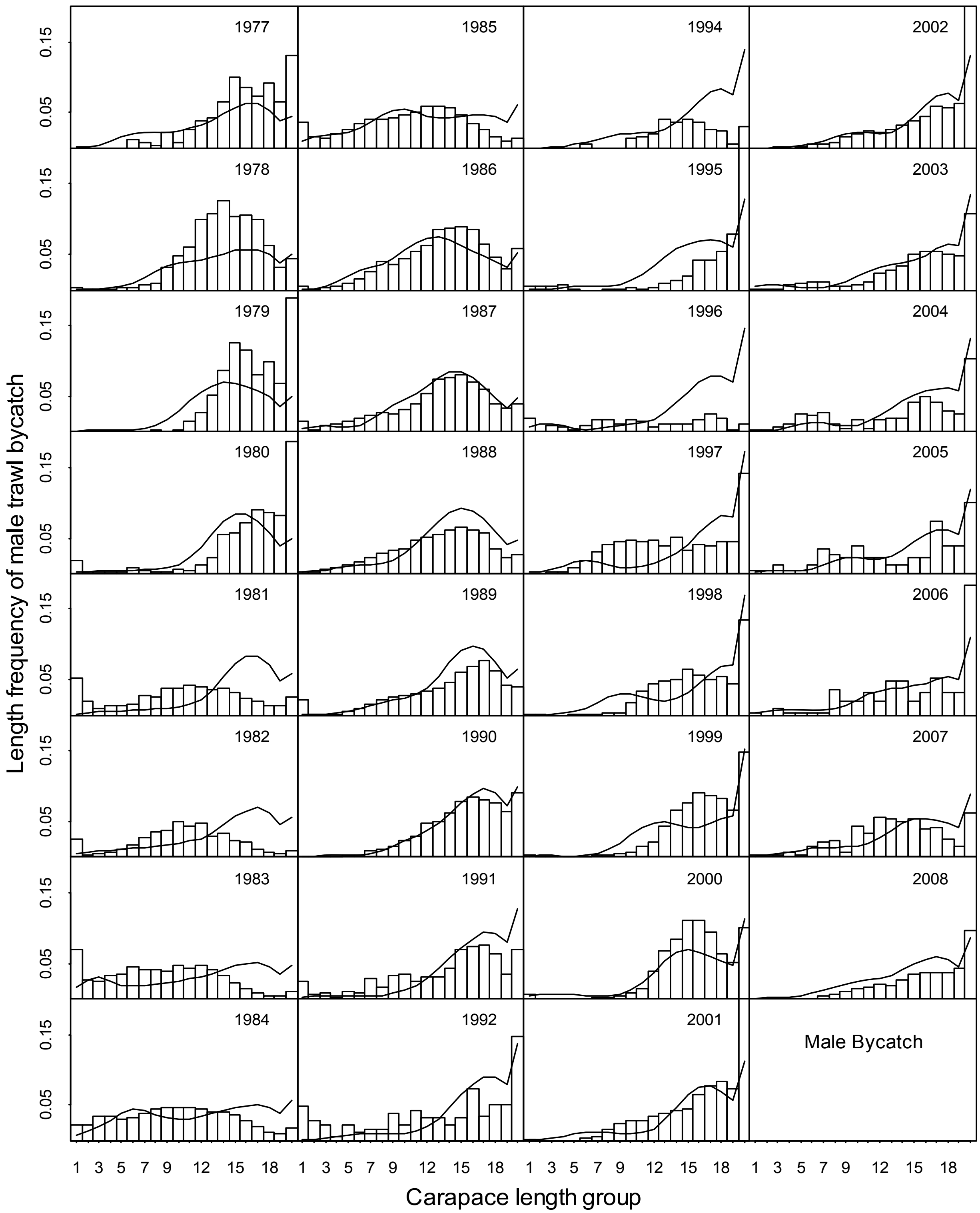


Figure 23(0). Comparison of observer and model estimated discarded length frequencies of Bristol Bay male red king crabs by year in the groundfish trawl fisheries under scenario 0. Pot handling mortality rate is 0.2, trawl bycatch mortality rate is 0.8, and the first length group is 67.5 mm.

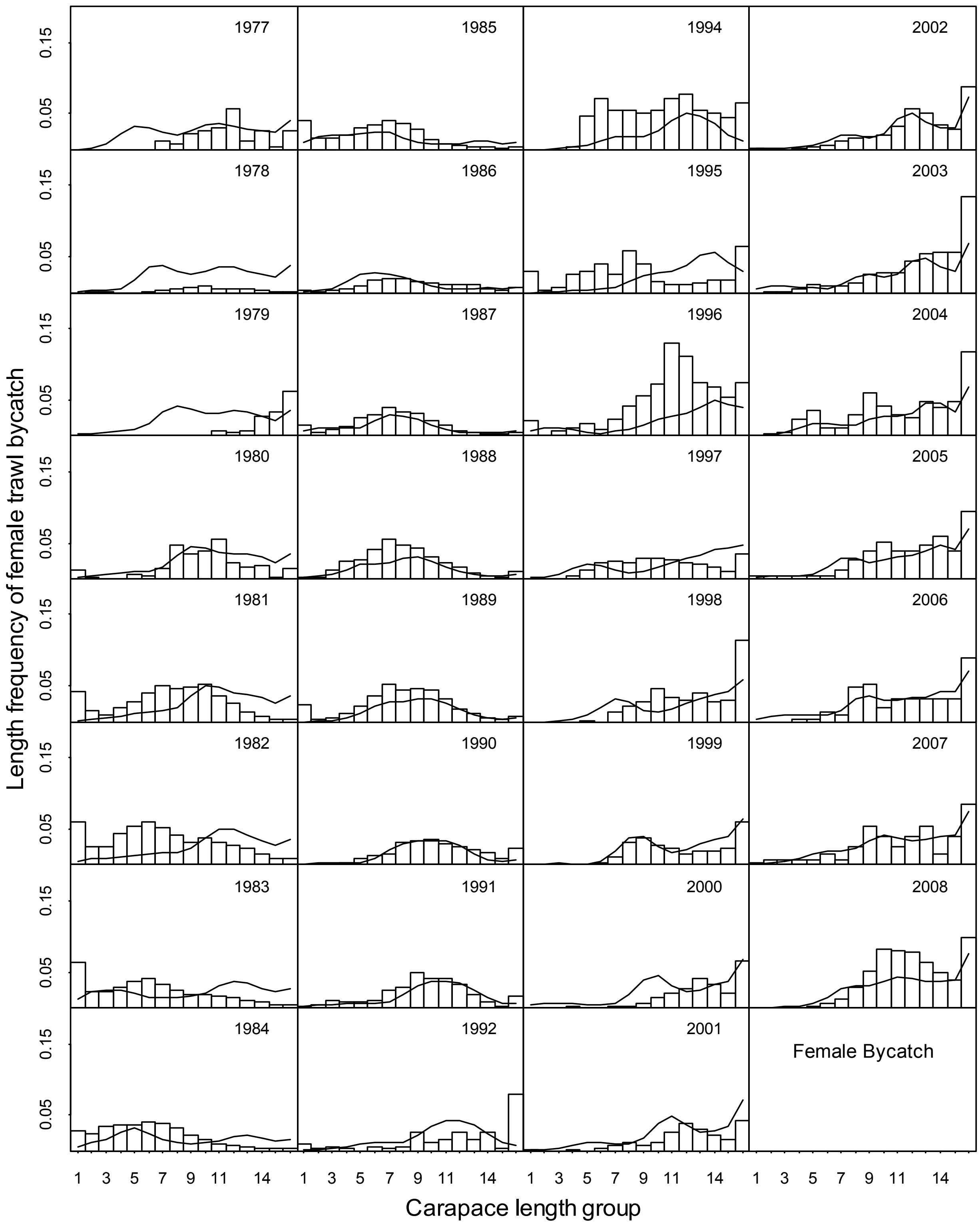


Figure 24(0). Comparison of observer and model estimated discarded length frequencies of Bristol Bay female red king crabs by year in the groundfish trawl fisheries under scenario 0. Pot handling mortality rate is 0.2, trawl bycatch mortality rate is 0.8, and the first length group is 67.5 mm.

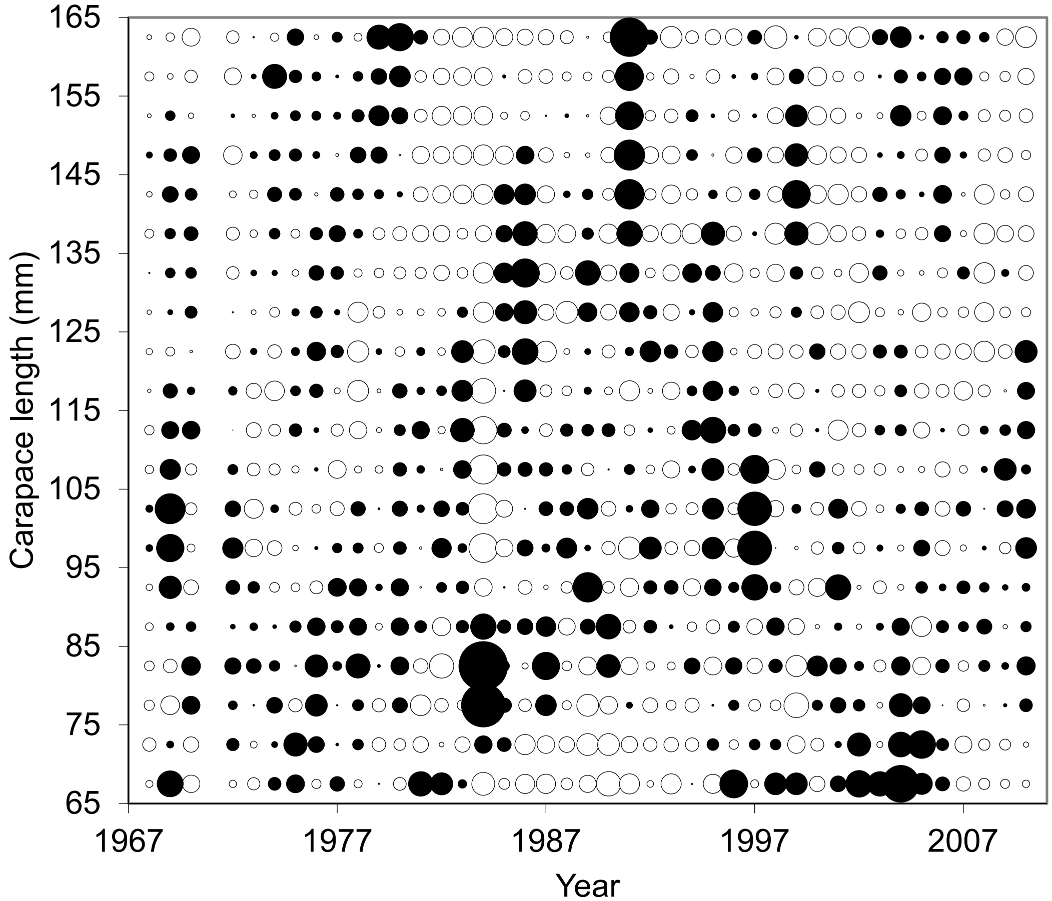


Figure 25(0). Standardized residuals of proportions of survey all-shell (1968-1985) and newshell (1986-2010) male red king crabs under scenario 0. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

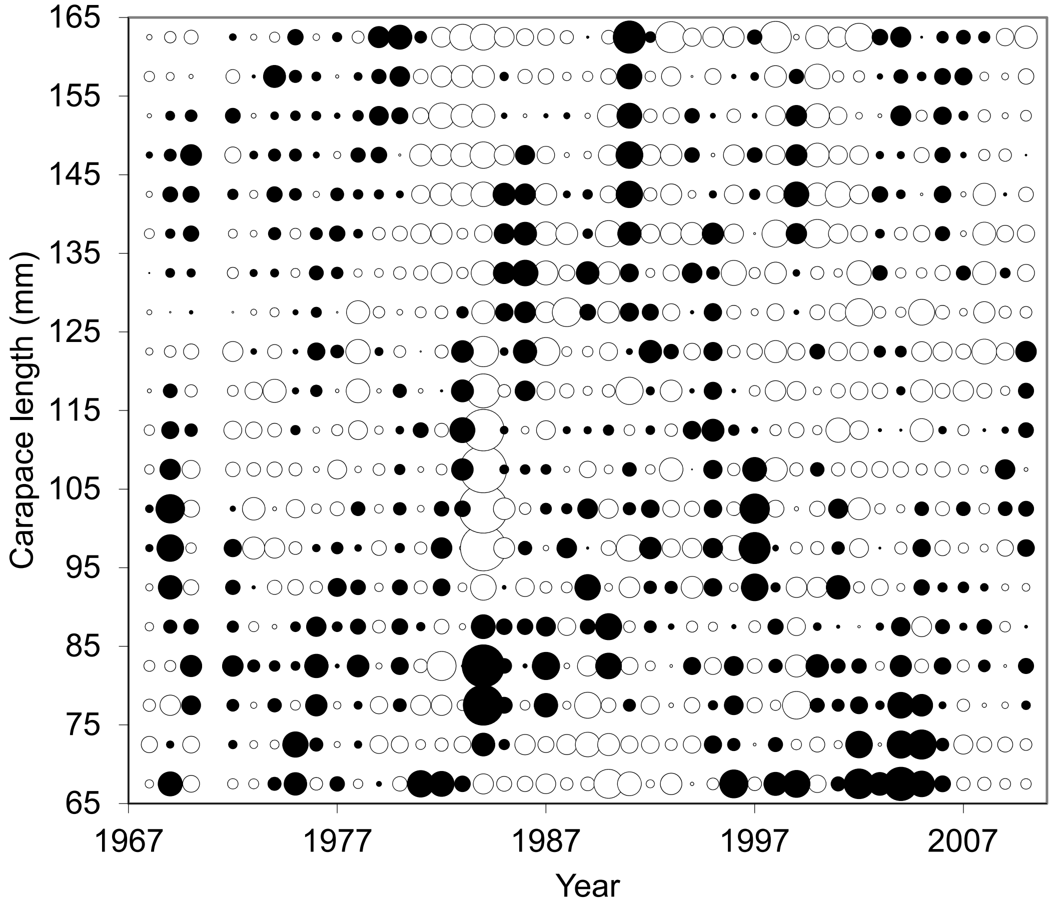


Figure 25(1). Standardized residuals of proportions of survey all-shell (1968-1985) and newshell (1986-2010) male red king crabs under scenario 1. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

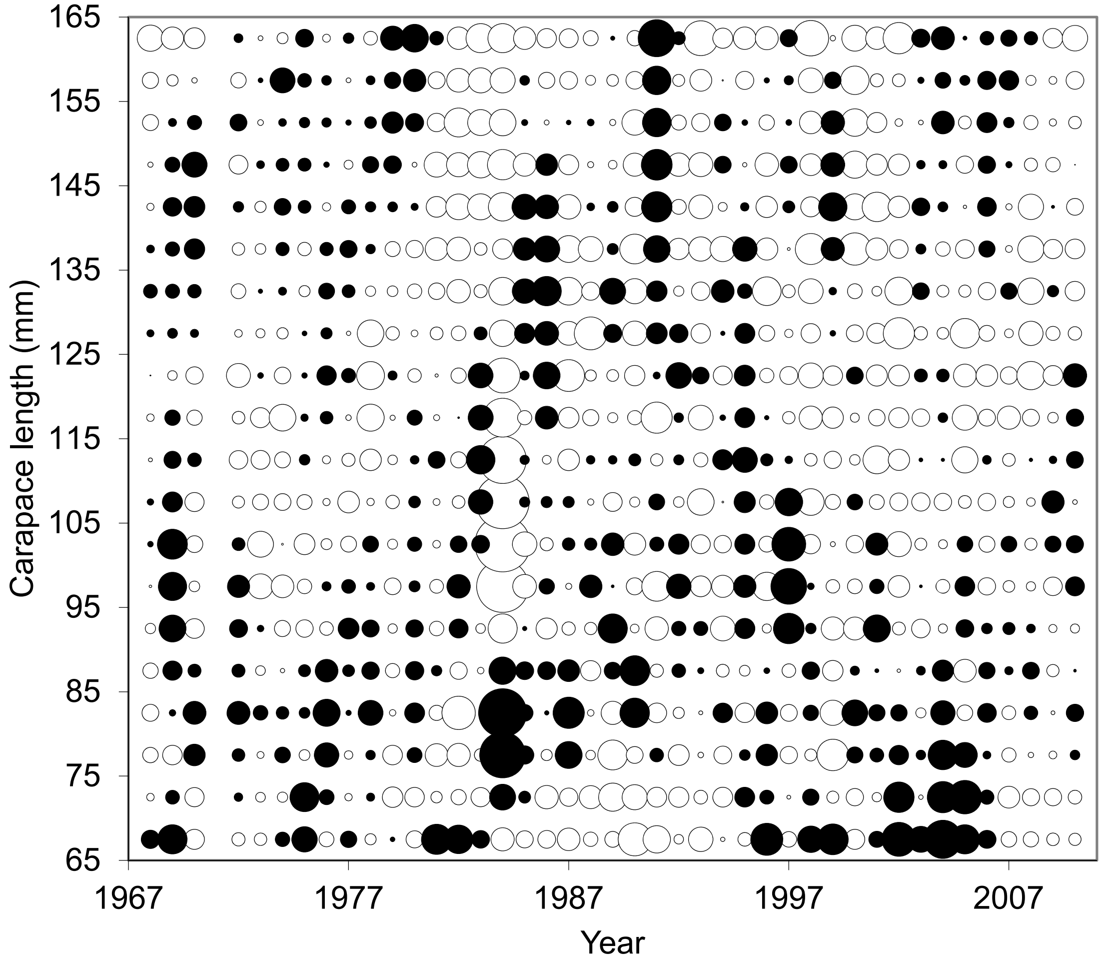


Figure 25(1a). Standardized residuals of proportions of survey all-shell (1968-1985) and newshell (1986-2010) male red king crabs under scenario 1a. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

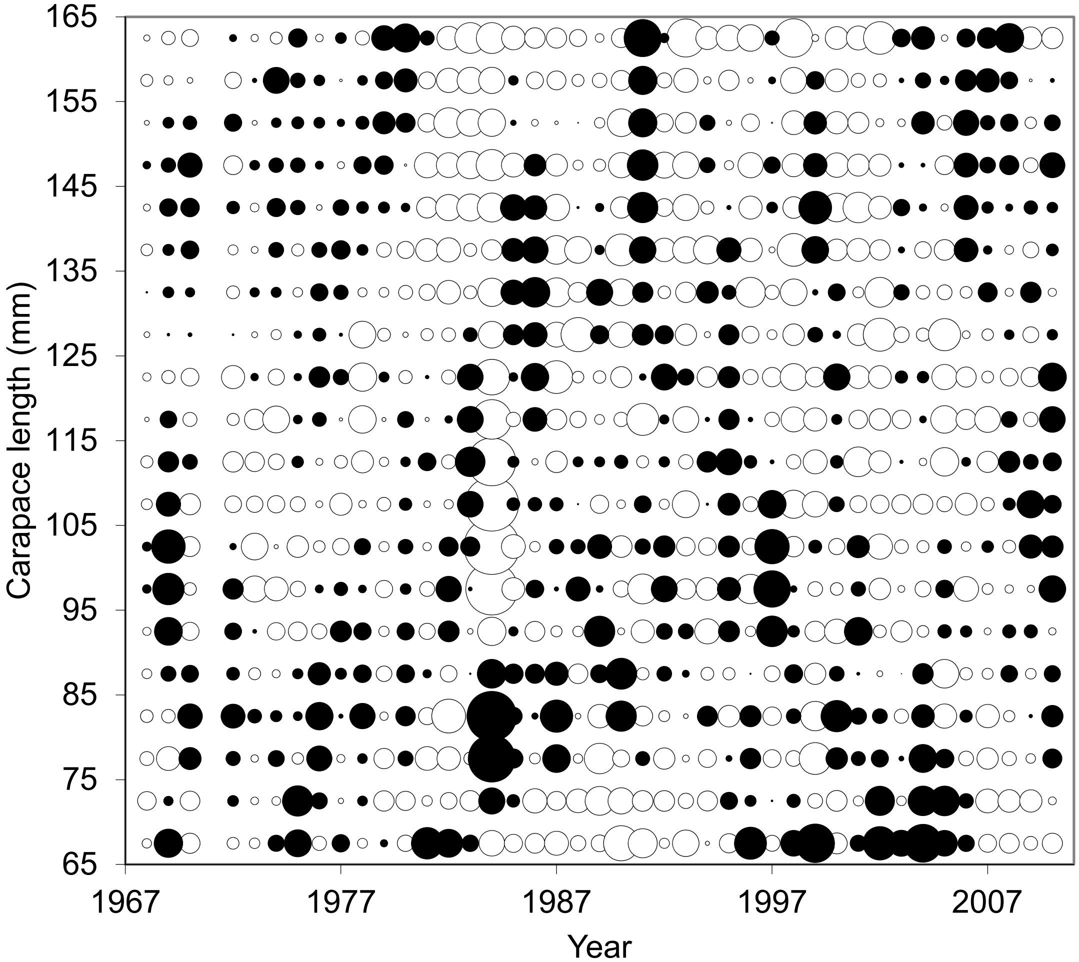


Figure 25(1b). Standardized residuals of proportions of survey all-shell (1968-1985) and newshell (1986-2010) male red king crabs under scenario 1b. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

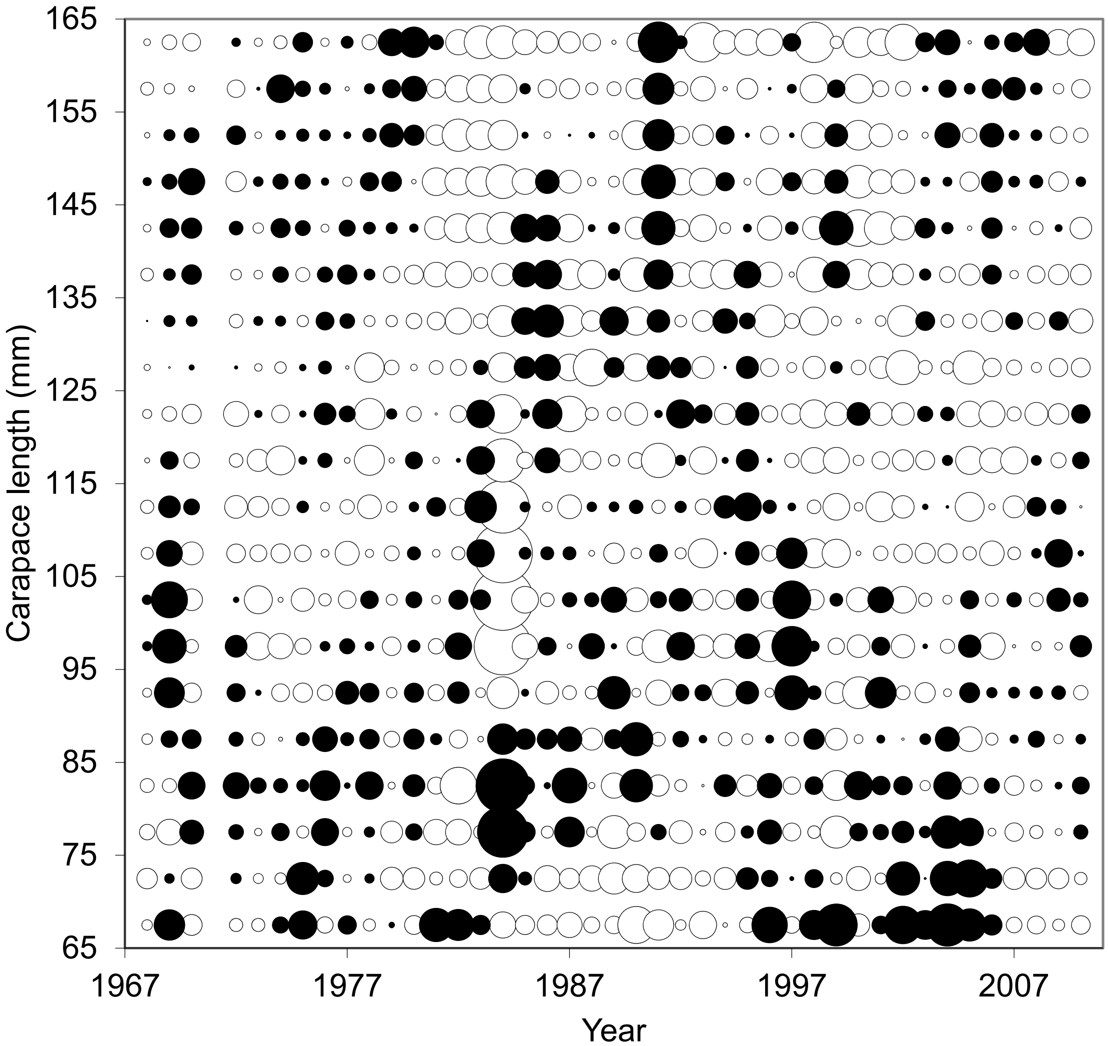


Figure 25(1c). Standardized residuals of proportions of survey all-shell (1968-1985) and newshell (1986-2010) male red king crabs under scenario 1c. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

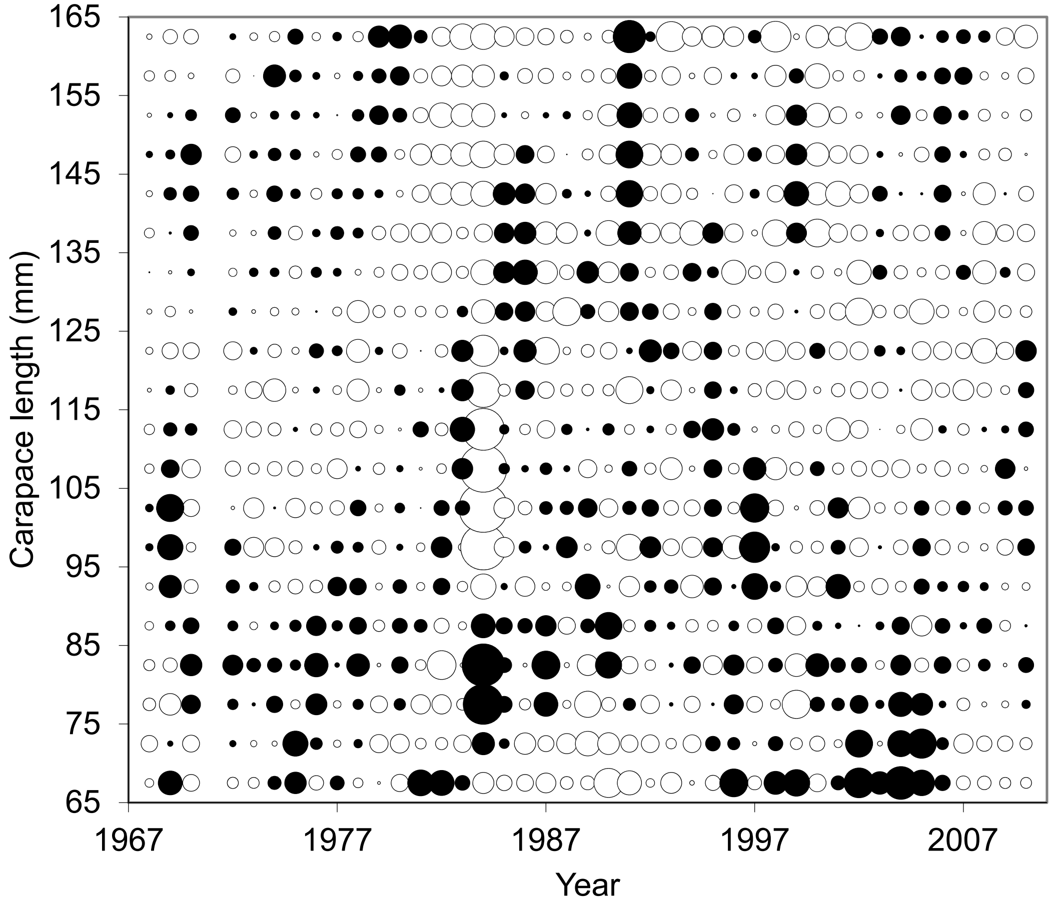


Figure 25(2). Standardized residuals of proportions of survey all-shell (1968-1985) and newshell (1986-2010) male red king crabs under scenario 2. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

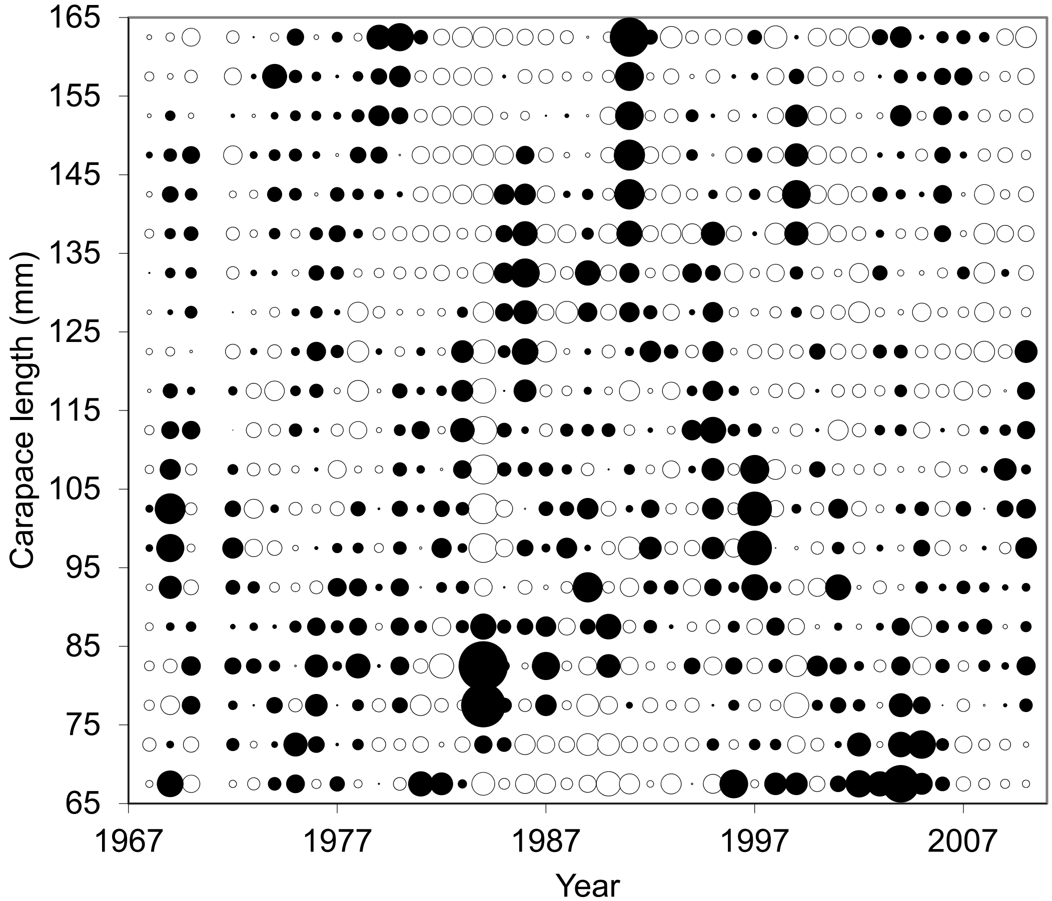


Figure 25(3). Standardized residuals of proportions of survey all-shell (1968-1985) and newshell (1986-2010) male red king crabs under scenario 3. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

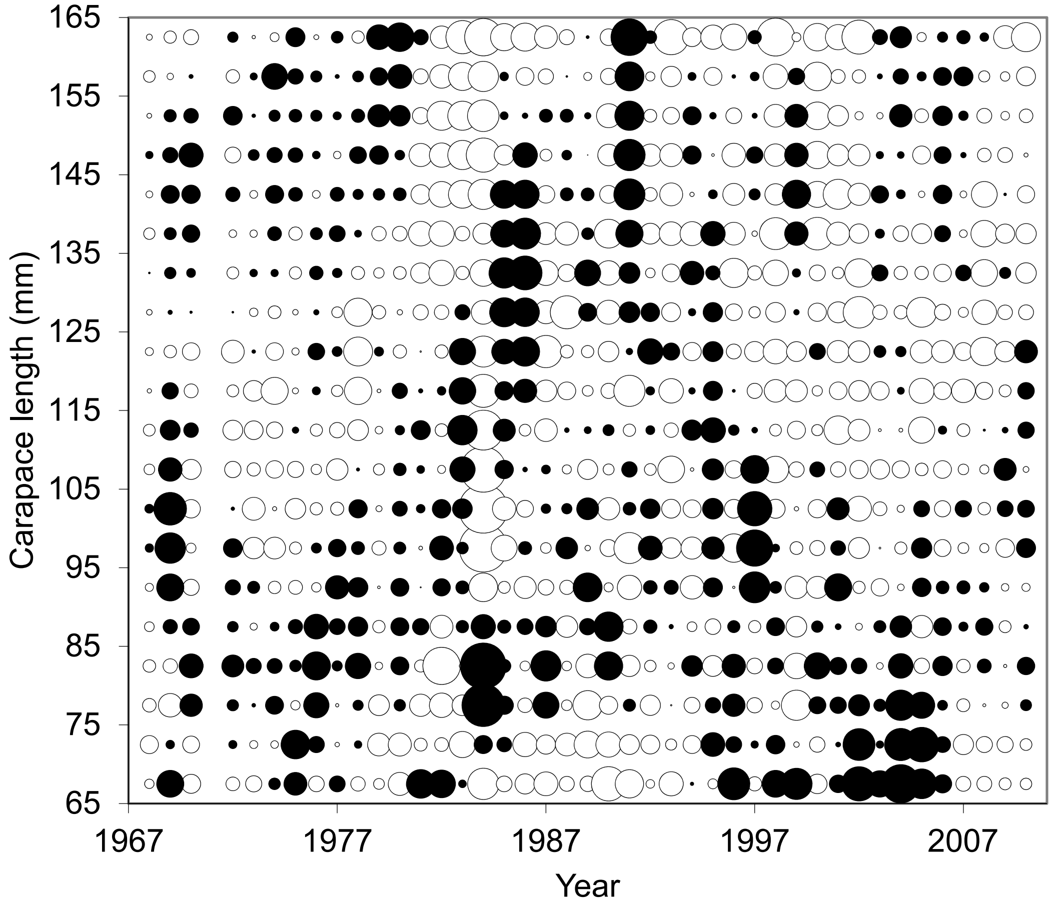


Figure 25(4). Standardized residuals of proportions of survey all-shell (1968-1985) and newshell (1986-2010) male red king crabs under scenario 4. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

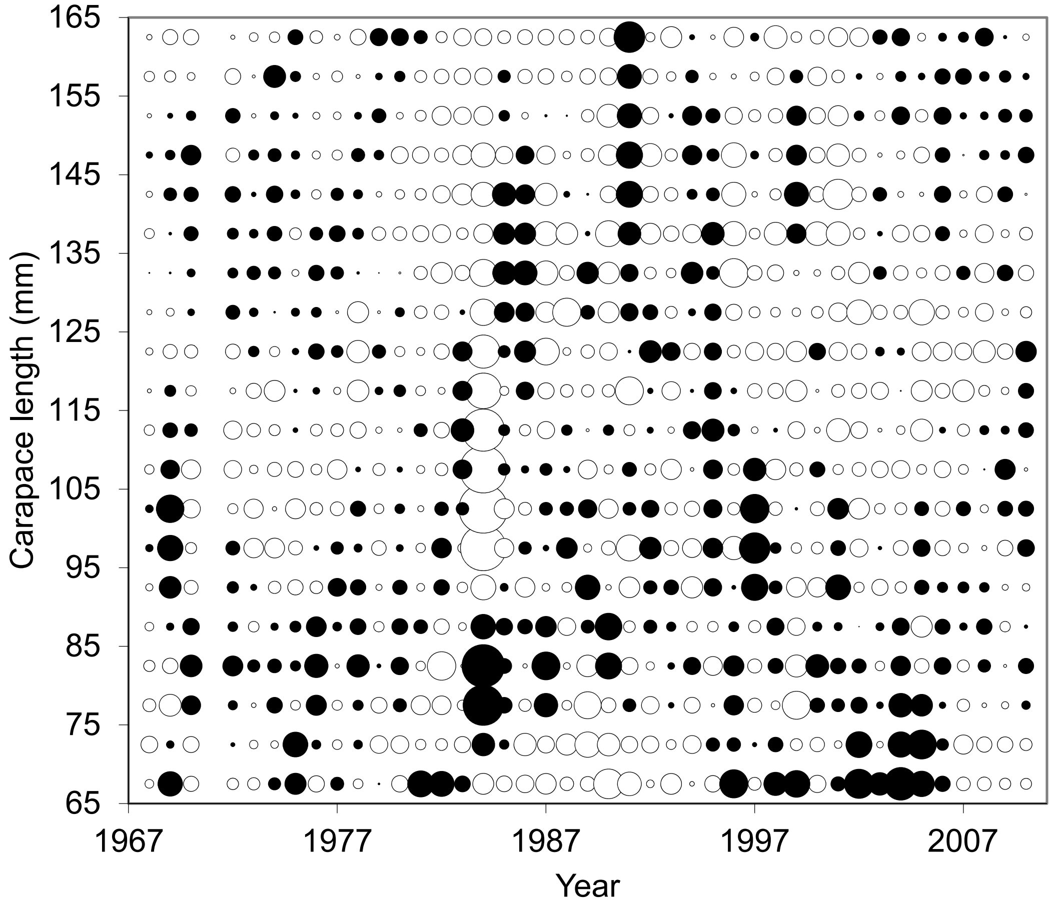


Figure 25(5). Standardized residuals of proportions of survey all-shell (1968-1985) and newshell (1986-2010) male red king crabs under scenario 5. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

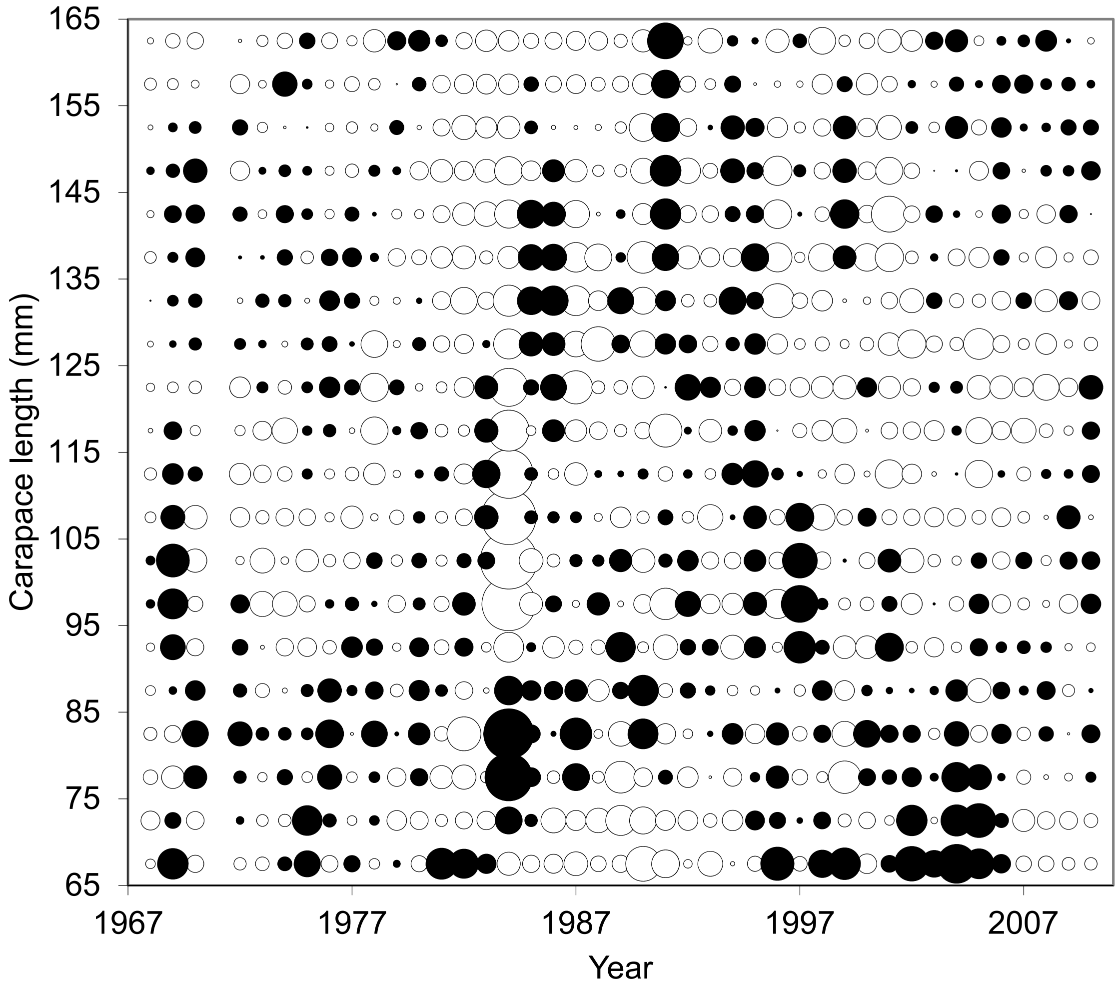


Figure 25(6). Standardized residuals of proportions of survey all-shell (1968-1985) and newshell (1986-2010) male red king crabs under scenario 6. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

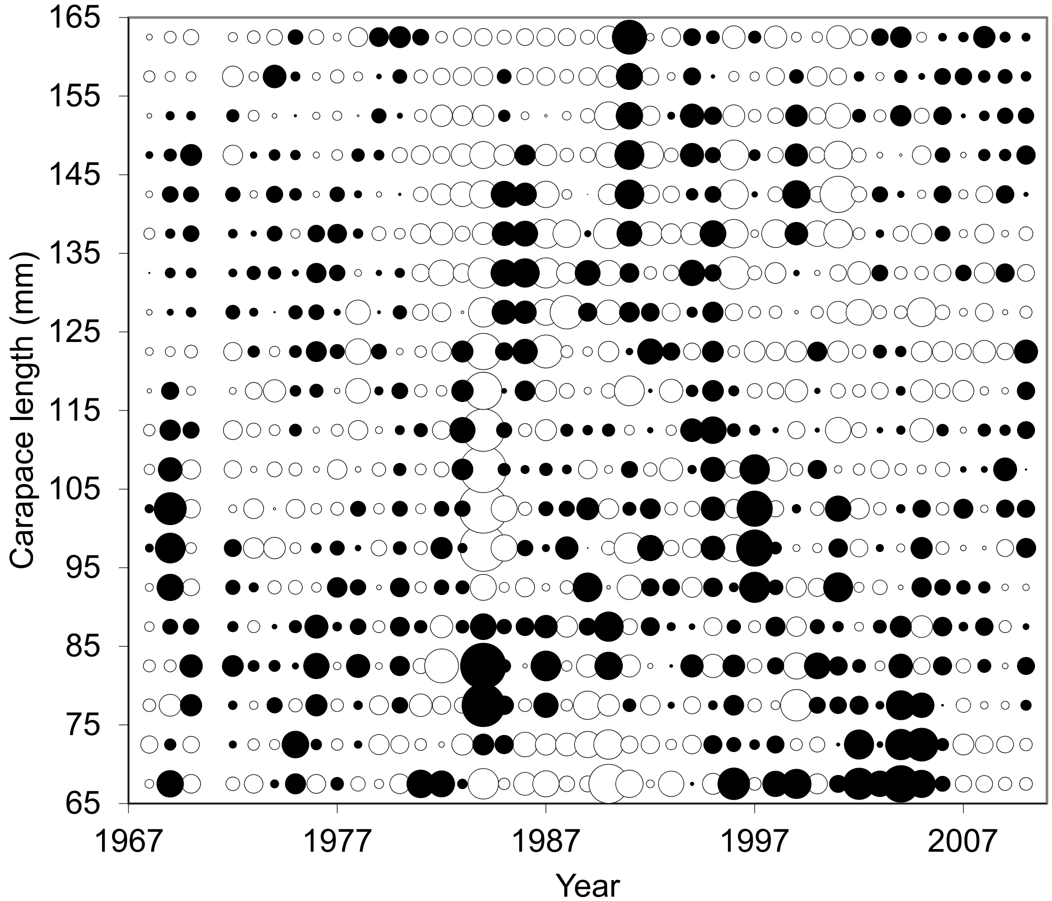


Figure 25(7). Standardized residuals of proportions of survey all-shell (1968-1985) and newshell (1986-2010) male red king crabs under scenario 7. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

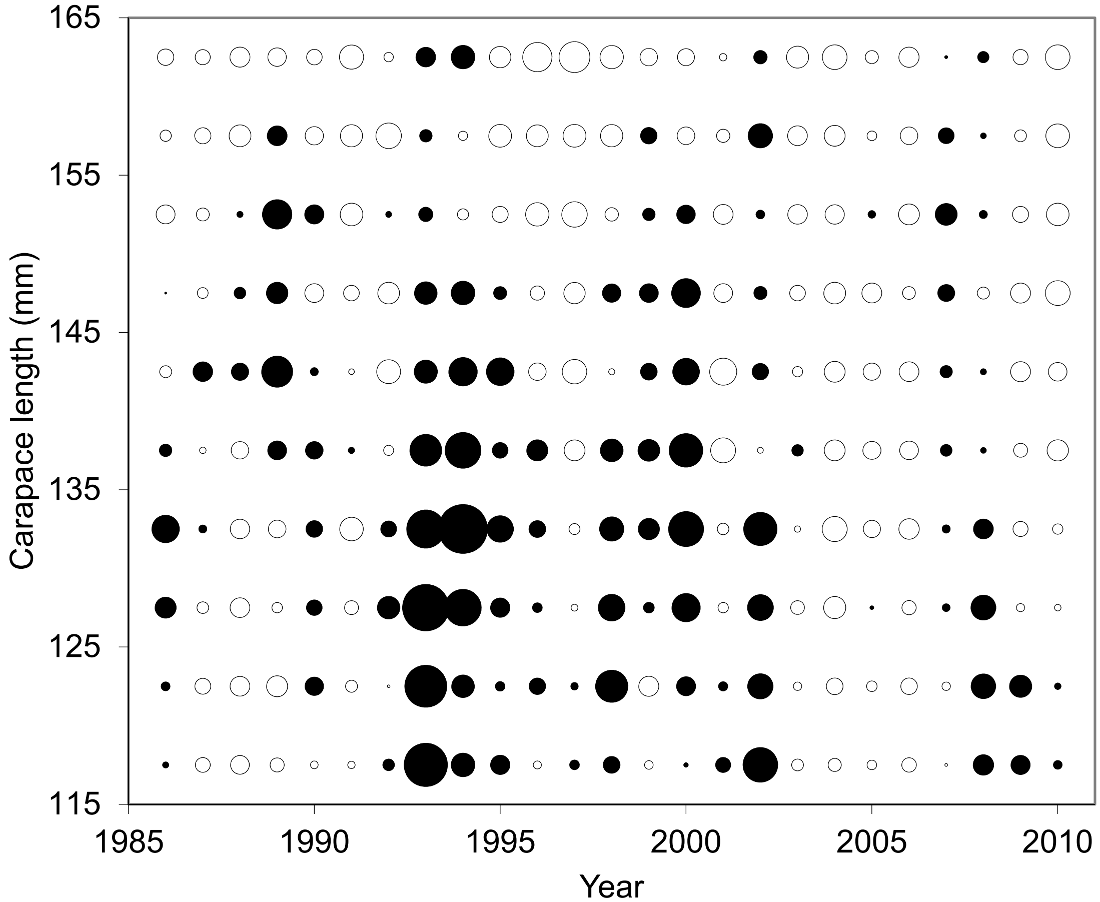


Figure 26(0). Standardized residuals of proportions of survey oldshell male red king crabs (1986-2010) under scenario 0. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

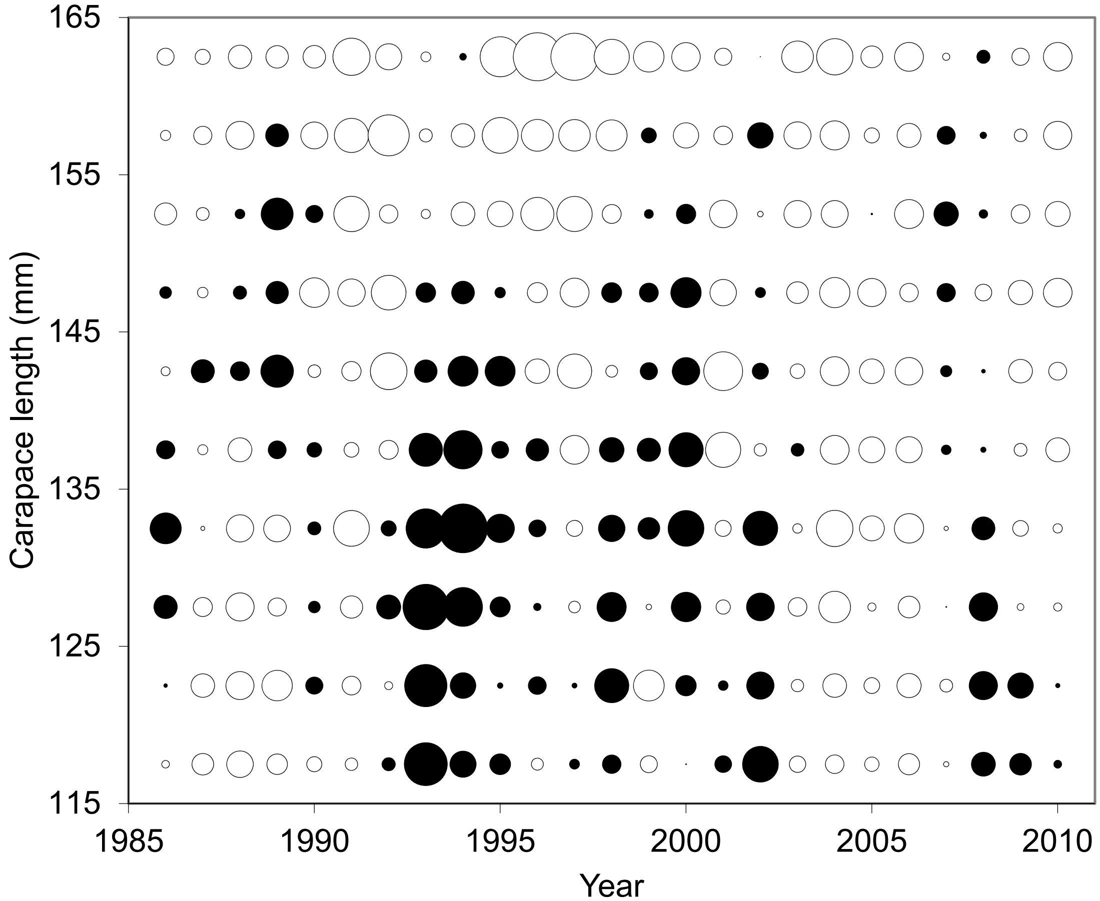


Figure 26(1). Standardized residuals of proportions of survey oldshell male red king crabs (1986-2010) under scenario 1. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

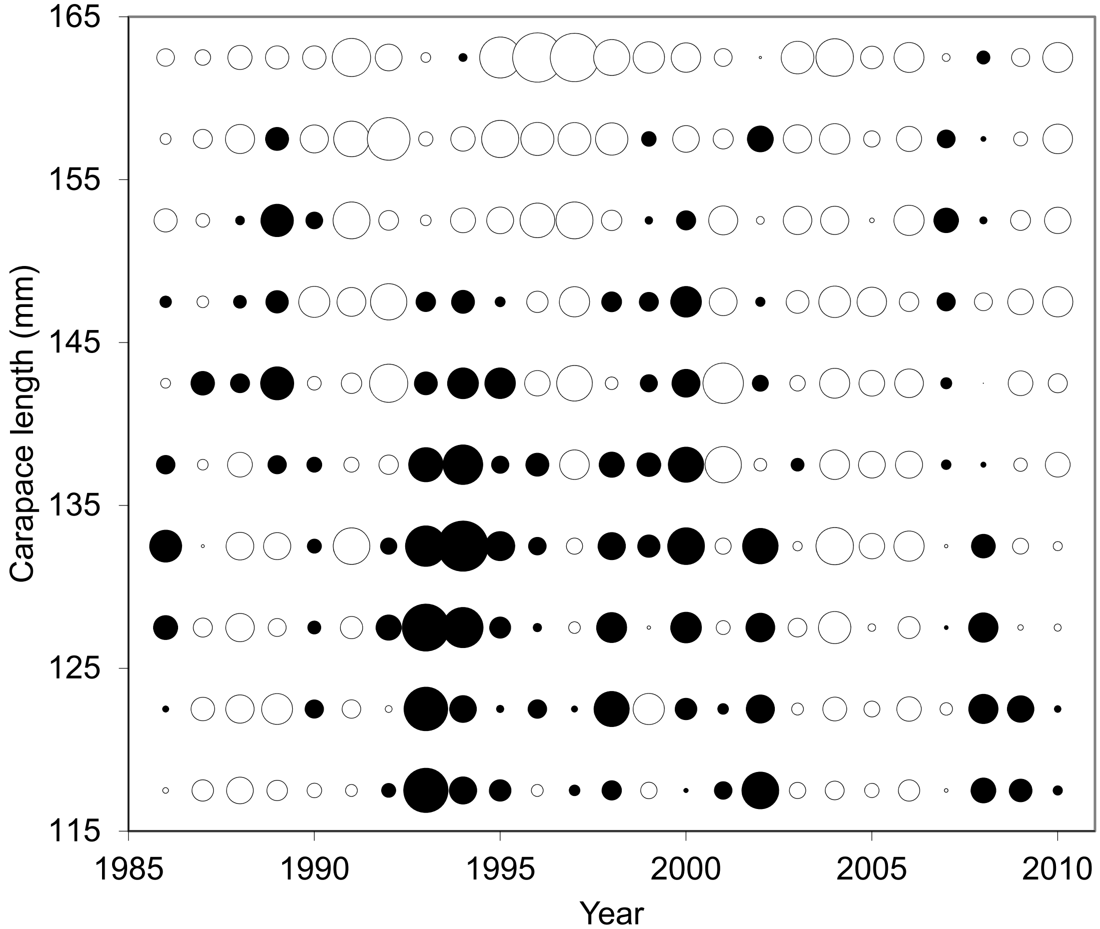


Figure 26(1a). Standardized residuals of proportions of survey oldshell male red king crabs (1986-2010) under scenario 1a. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

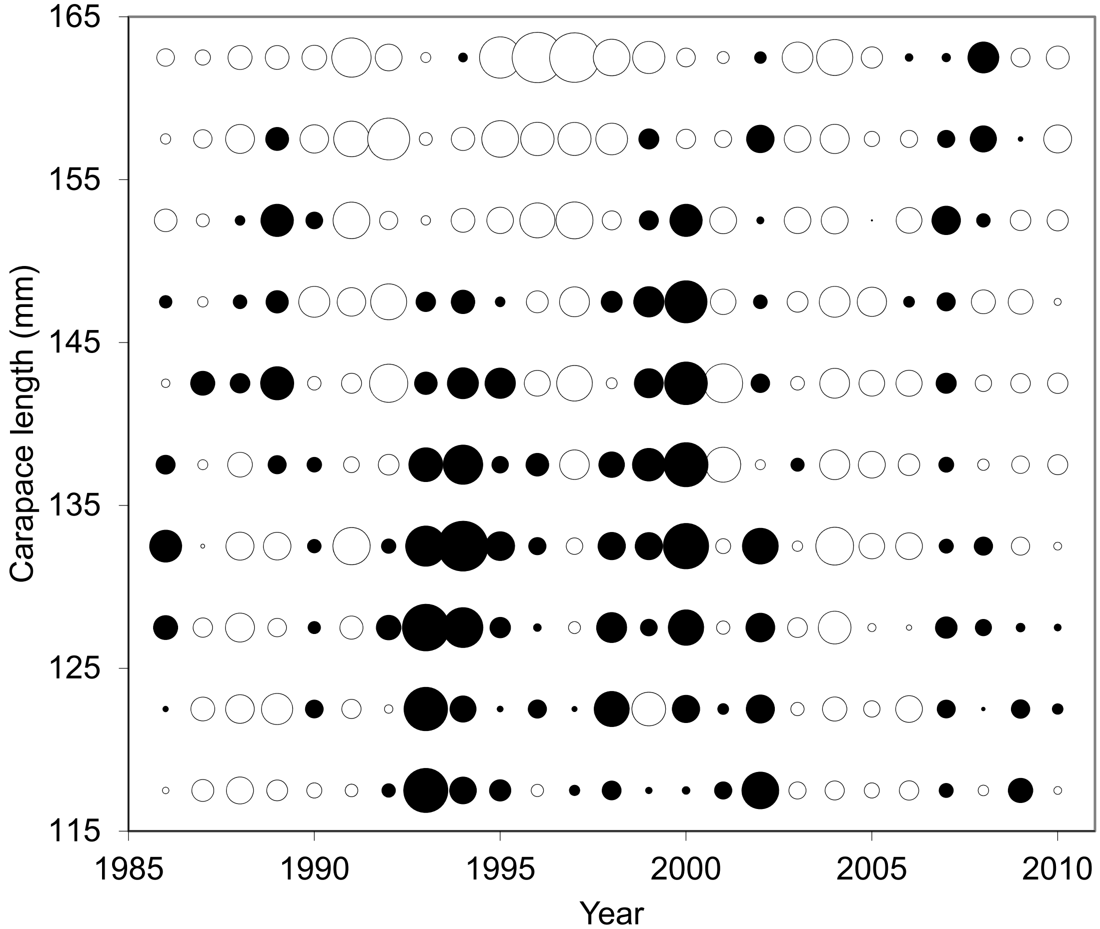


Figure 26(1b). Standardized residuals of proportions of survey oldshell male red king crabs (1986-2010) under scenario 1b. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

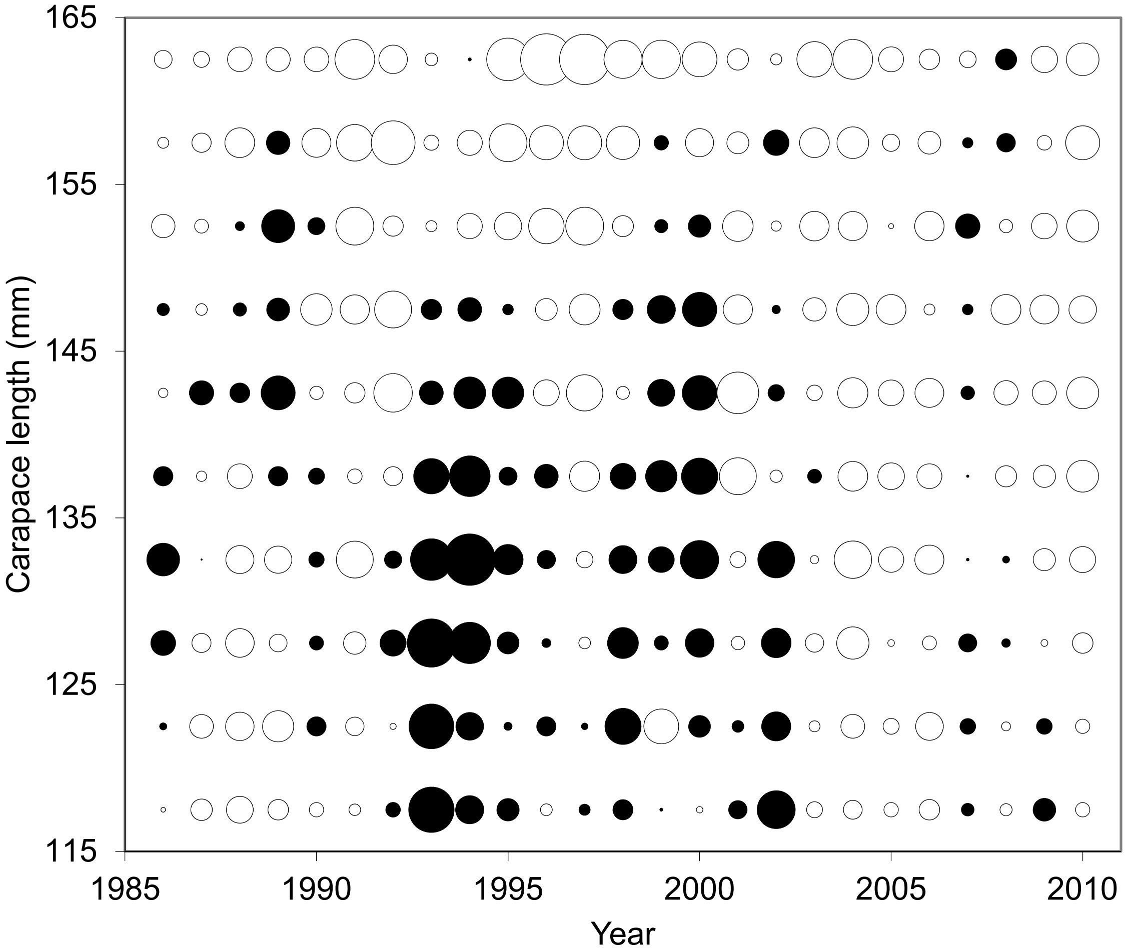


Figure 26(1c). Standardized residuals of proportions of survey oldshell male red king crabs (1986-2010) under scenario 1c. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

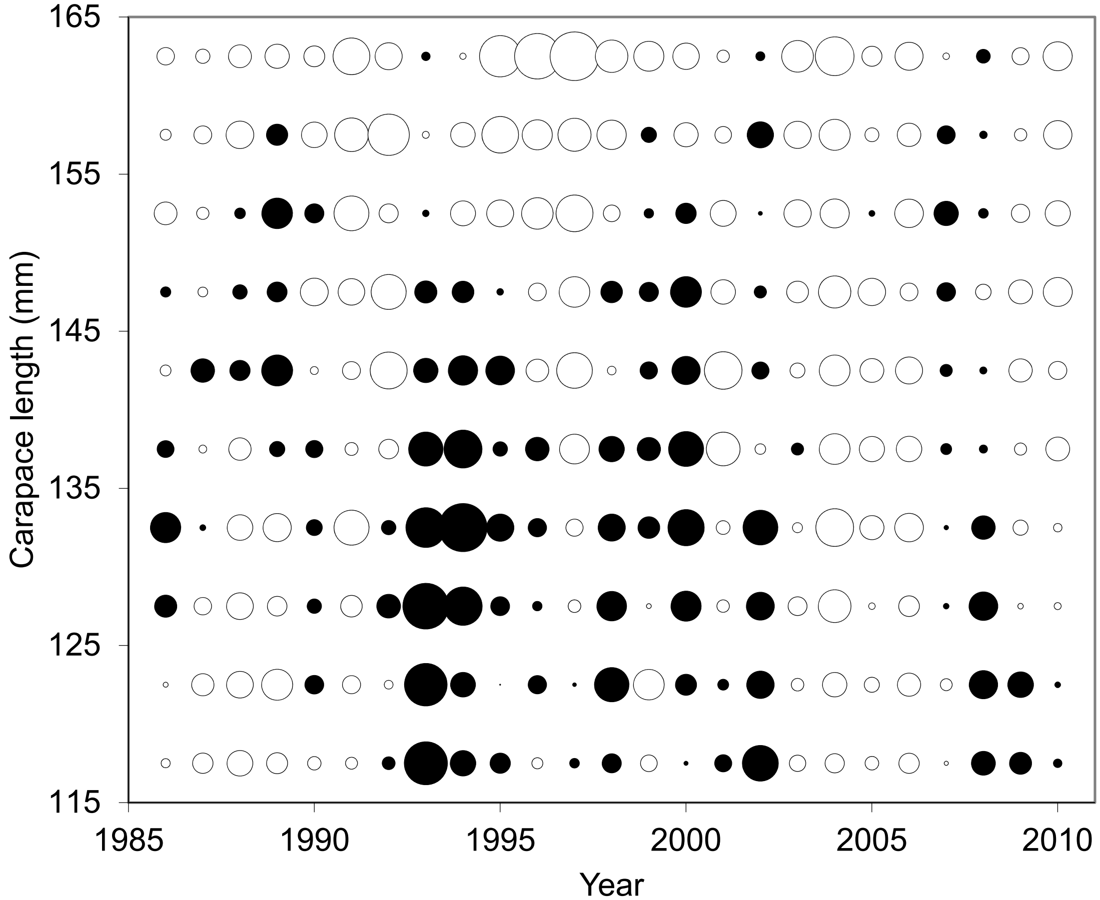


Figure 26(2). Standardized residuals of proportions of survey oldshell male red king crabs (1986-2010) under scenario 2. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

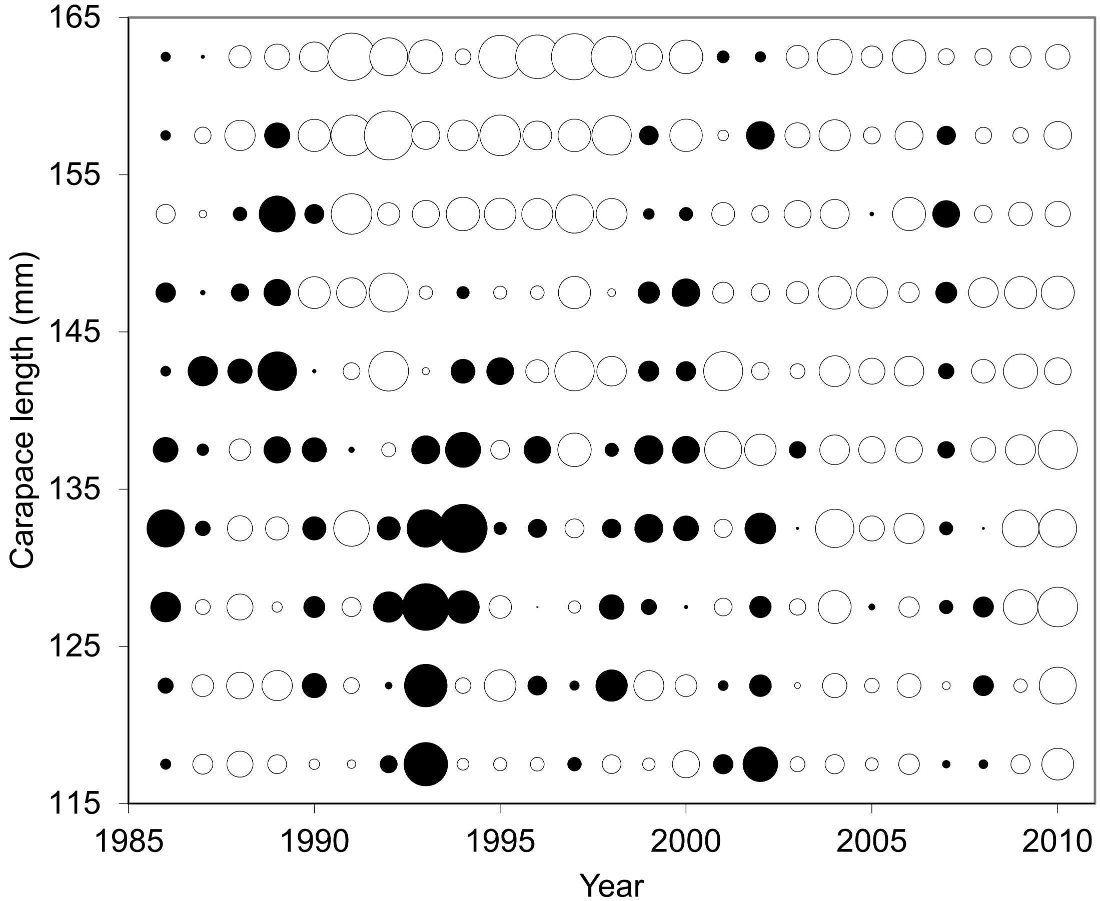


Figure 26(3). Standardized residuals of proportions of survey oldshell male red king crabs (1986-2010) under scenario 3. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

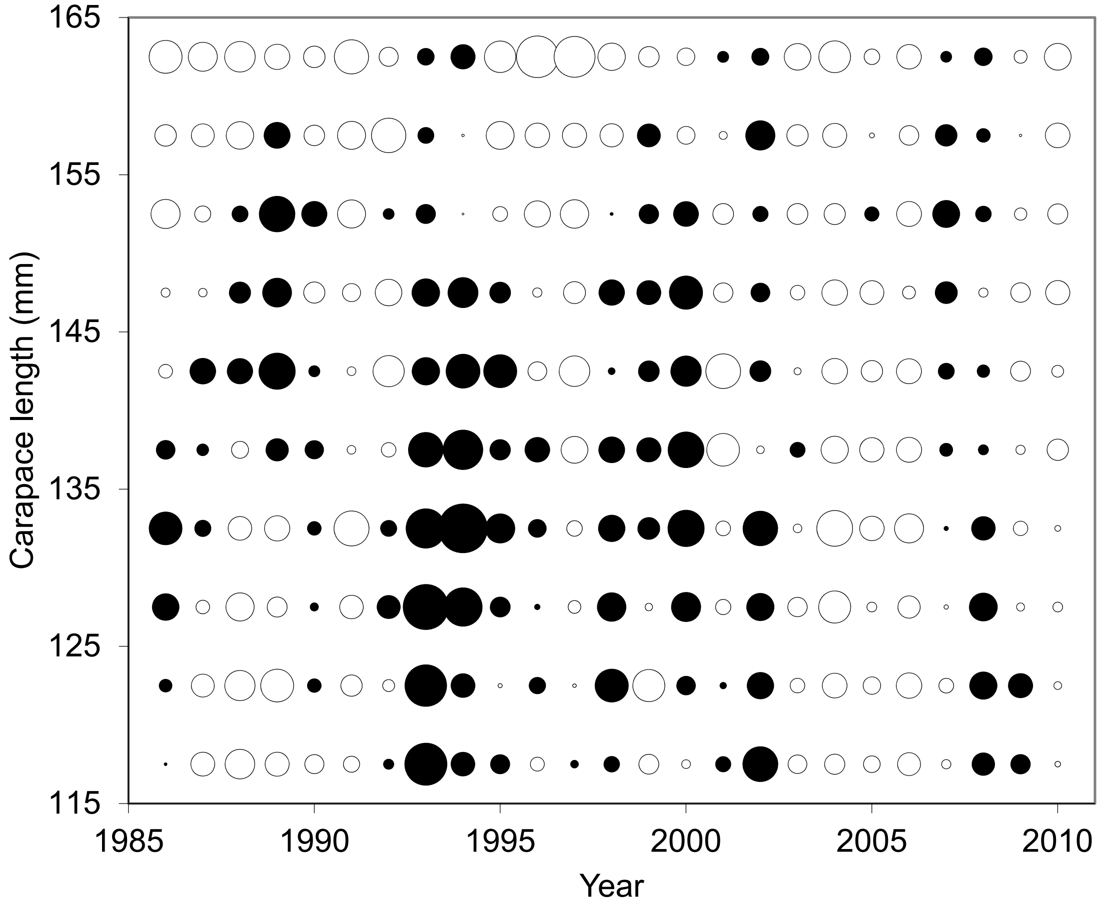


Figure 26(4). Standardized residuals of proportions of survey oldshell male red king crabs (1986-2010) under scenario 4. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

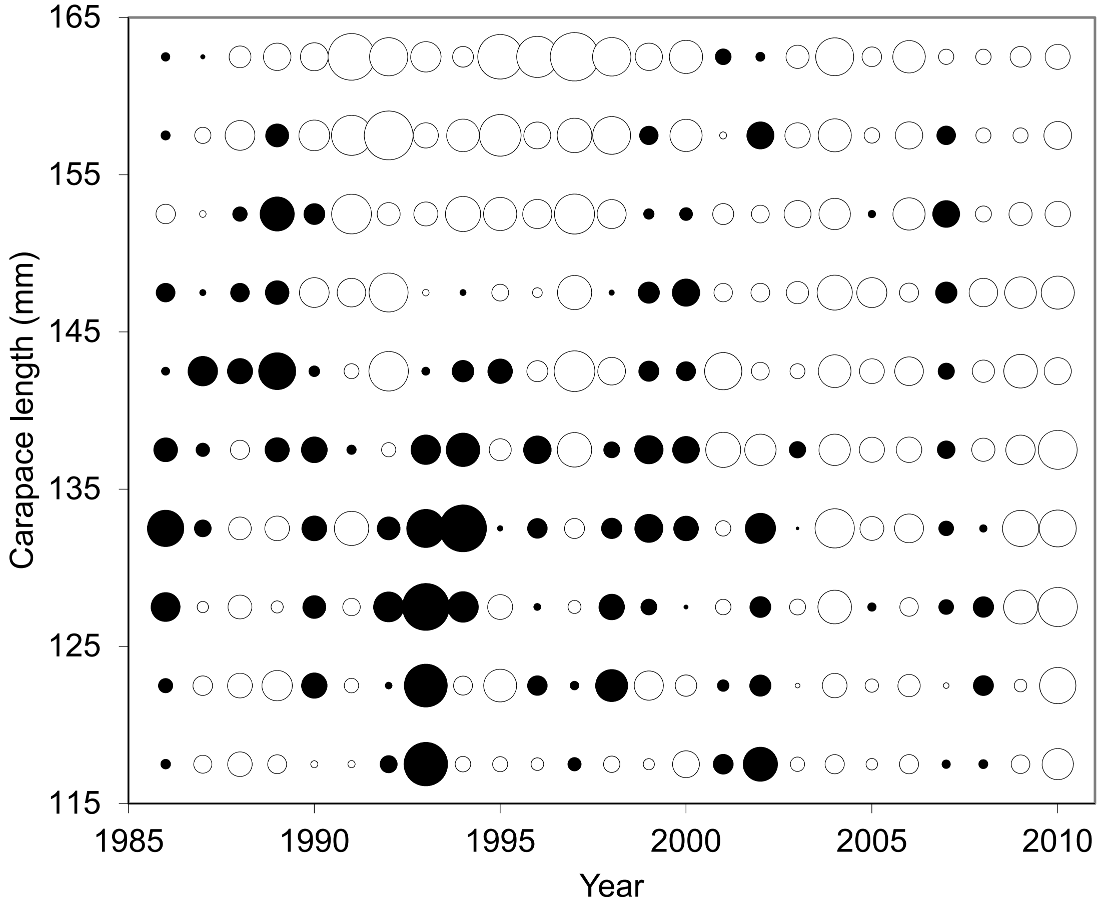


Figure 26(5). Standardized residuals of proportions of survey oldshell male red king crabs (1986-2010) under scenario 5. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

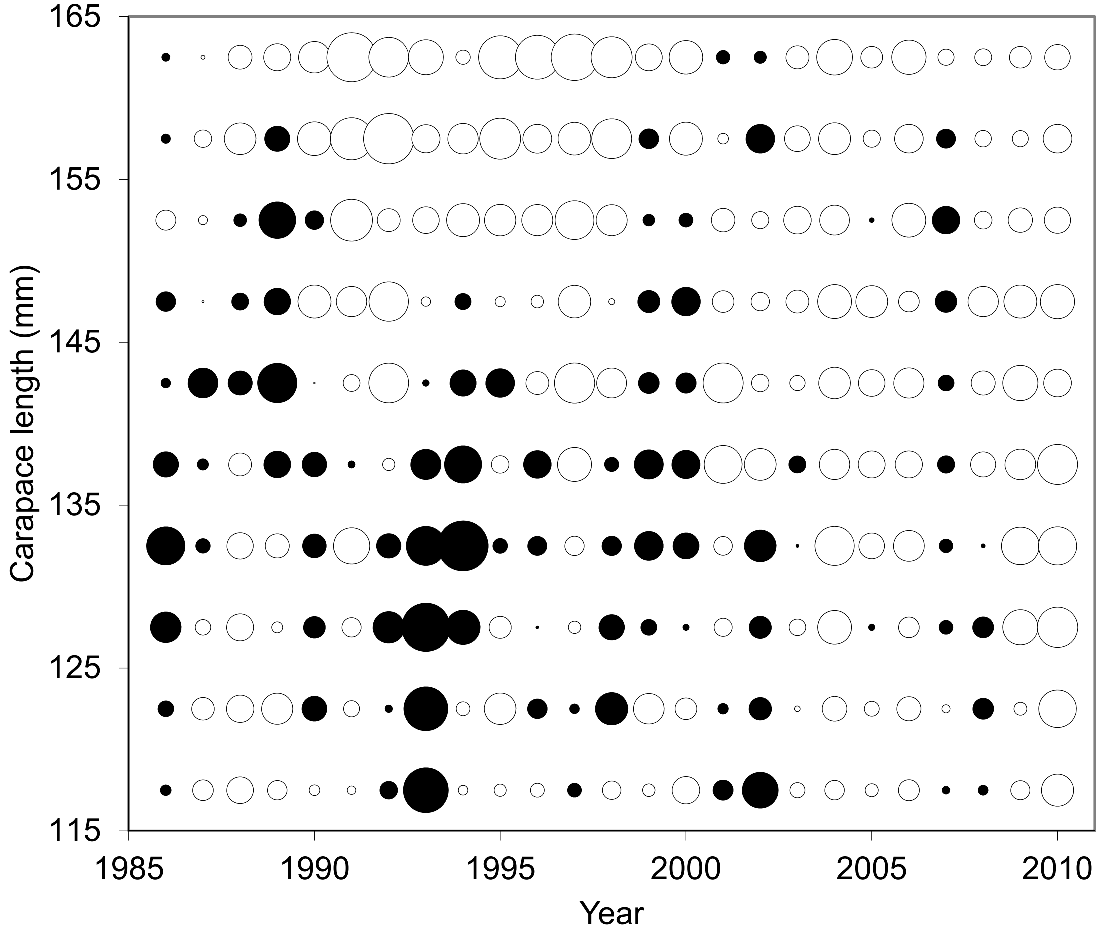


Figure 26(6). Standardized residuals of proportions of survey oldshell male red king crabs (1986-2010) under scenario 6. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

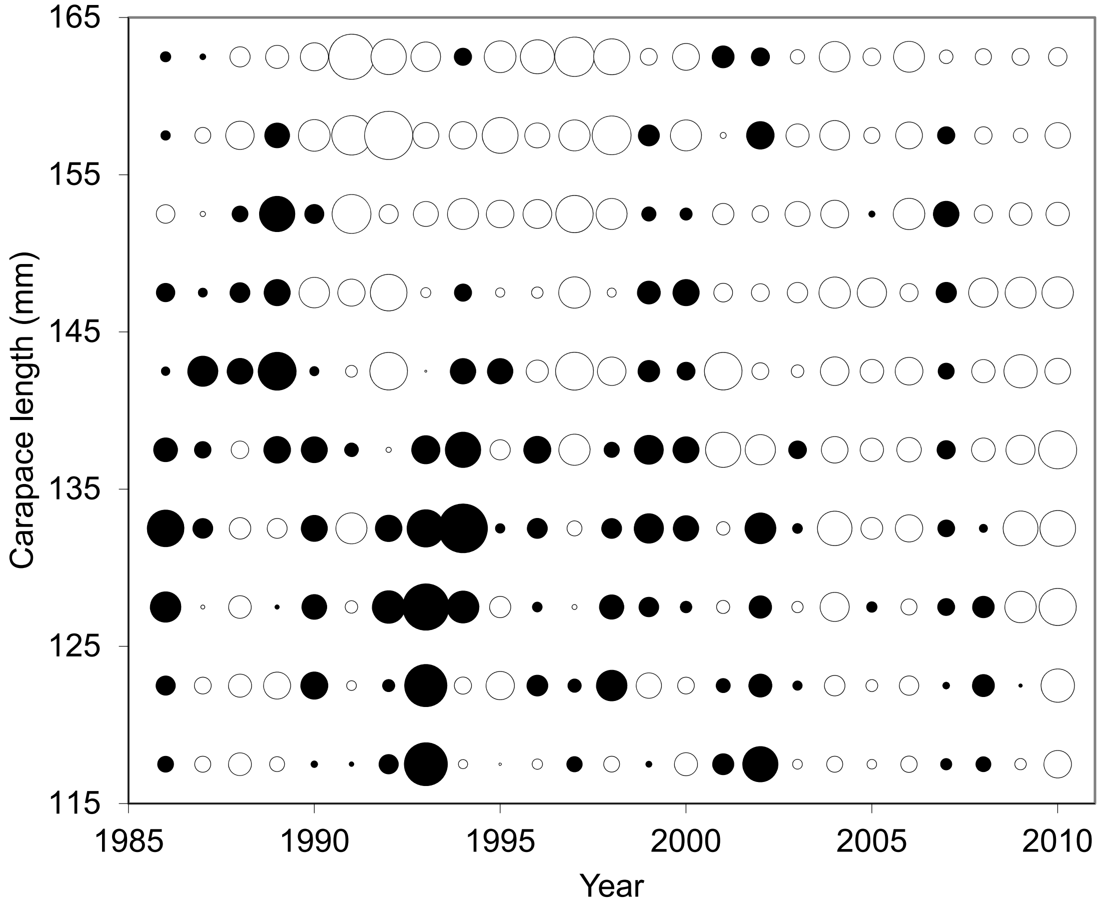


Figure 26(7). Standardized residuals of proportions of survey oldshell male red king crabs (1986-2010) under scenario 7. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

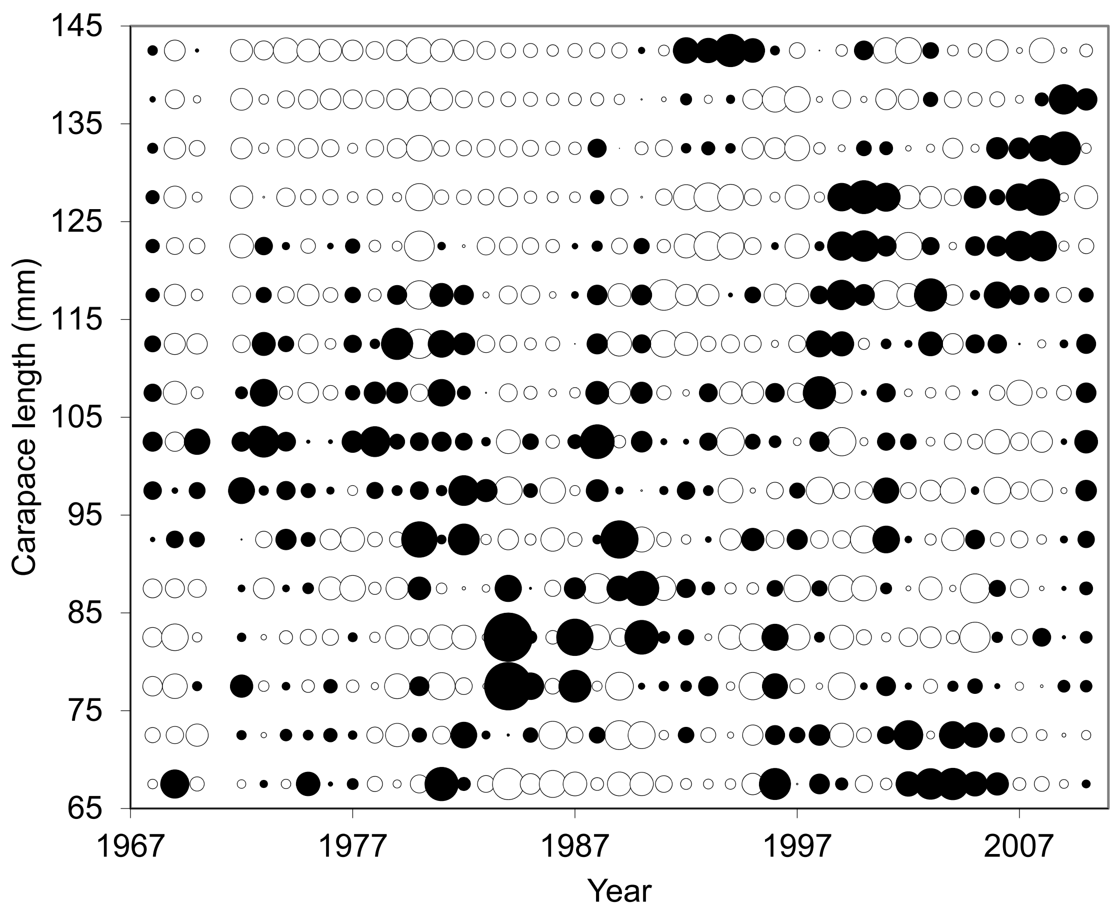


Figure 27(0). Standardized residuals of proportions of survey female red king crabs (1968-2010) under scenario 0. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

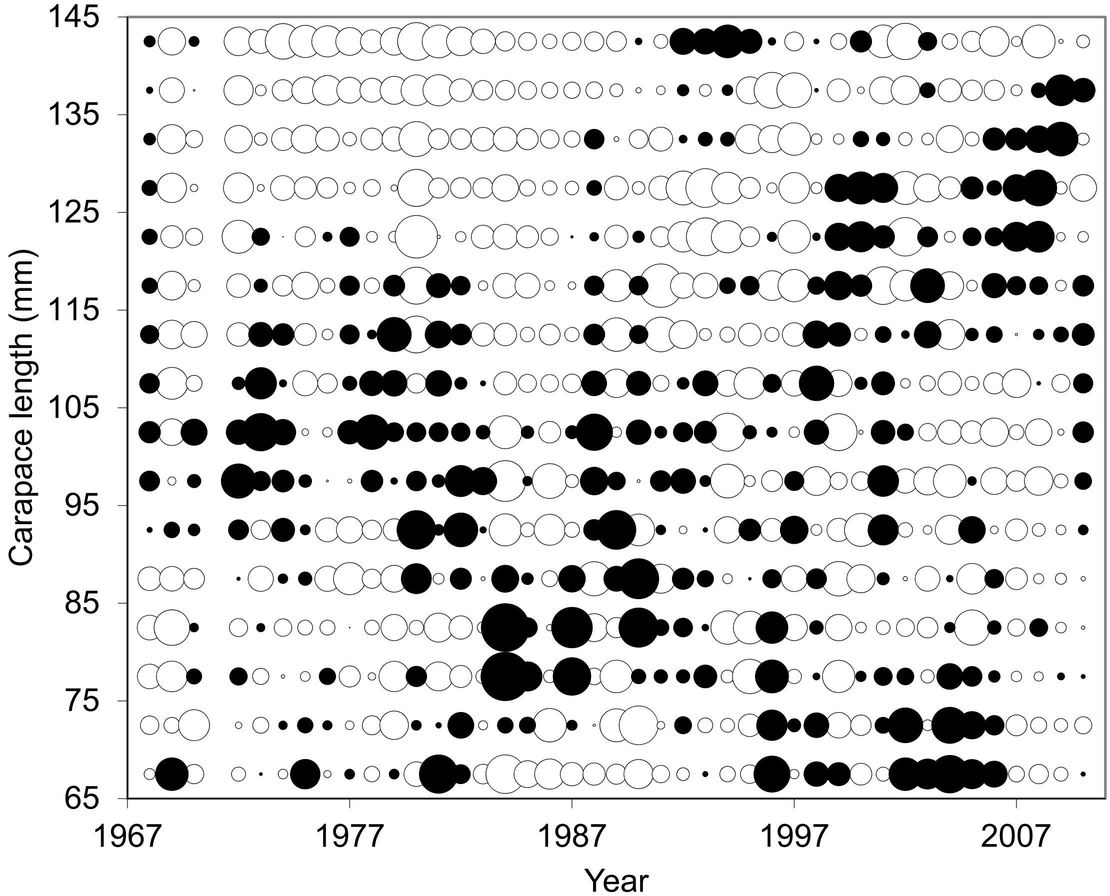


Figure 27(1). Standardized residuals of proportions of survey female red king crabs (1968-2010) under scenario 1. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

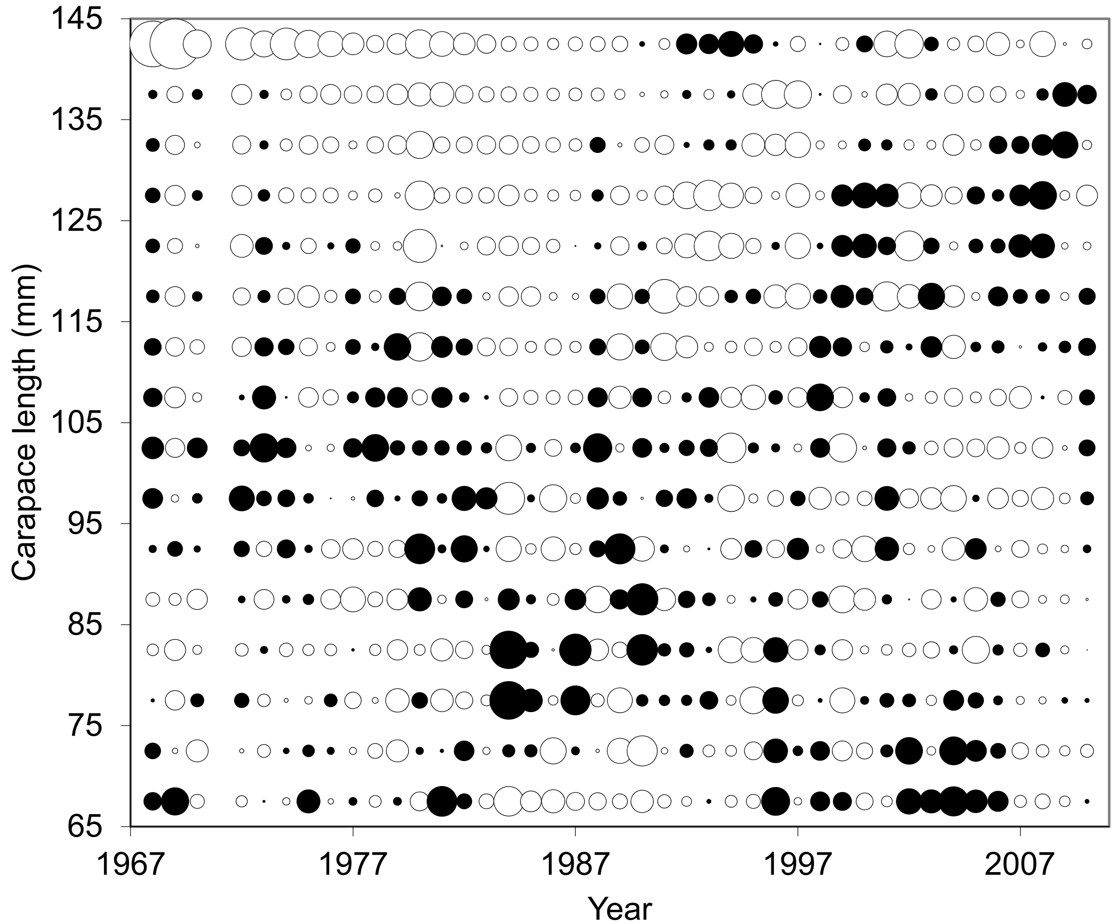


Figure 27(1a). Standardized residuals of proportions of survey female red king crabs (1968-2010) under scenario 1a. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

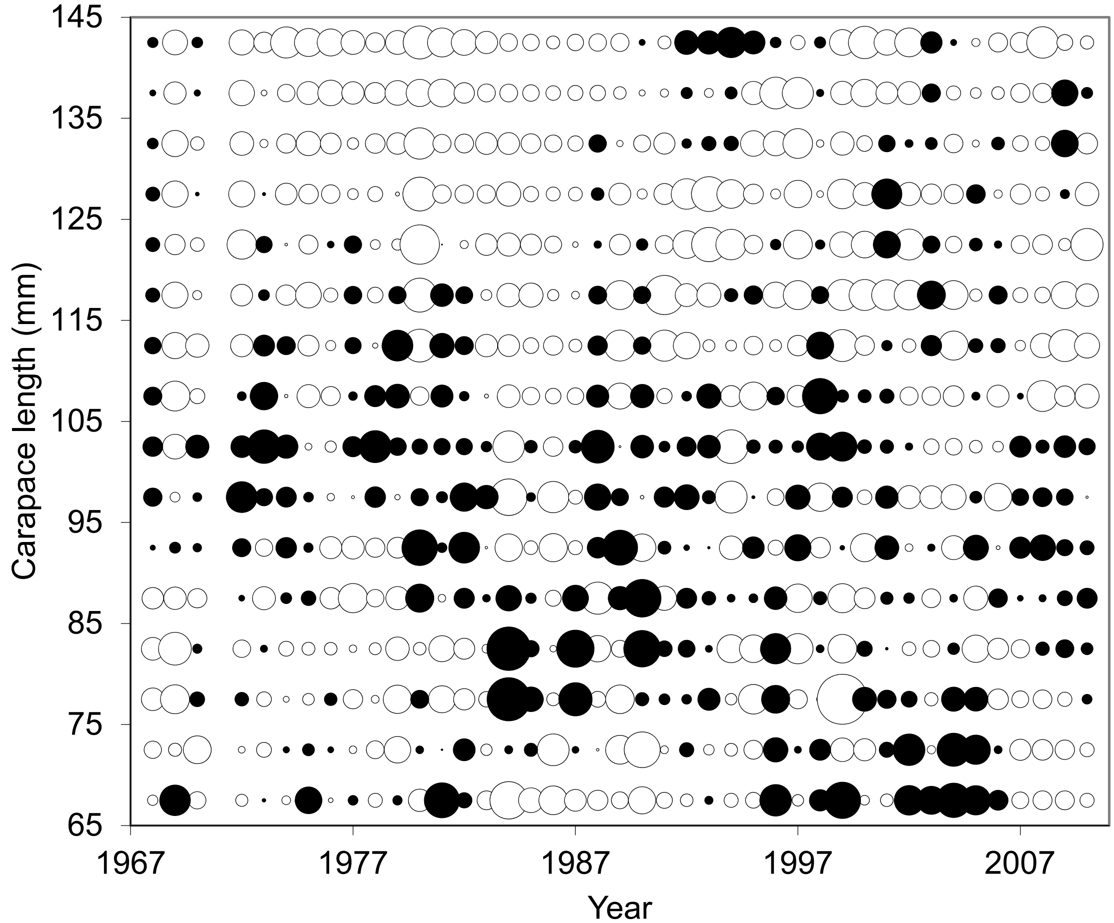


Figure 27(1b). Standardized residuals of proportions of survey female red king crabs (1968-2010) under scenario 1b. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

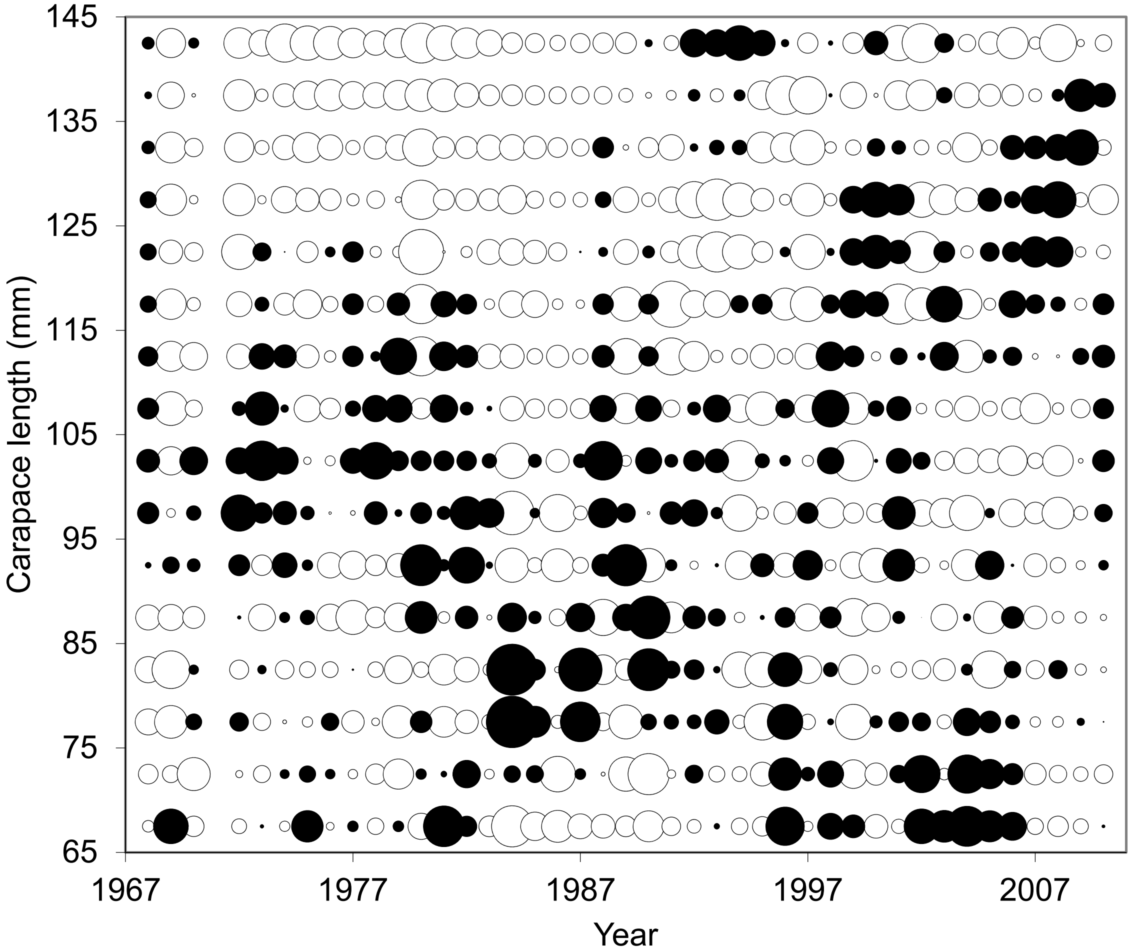


Figure 27(1c). Standardized residuals of proportions of survey female red king crabs (1968-2010) under scenario 1c. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

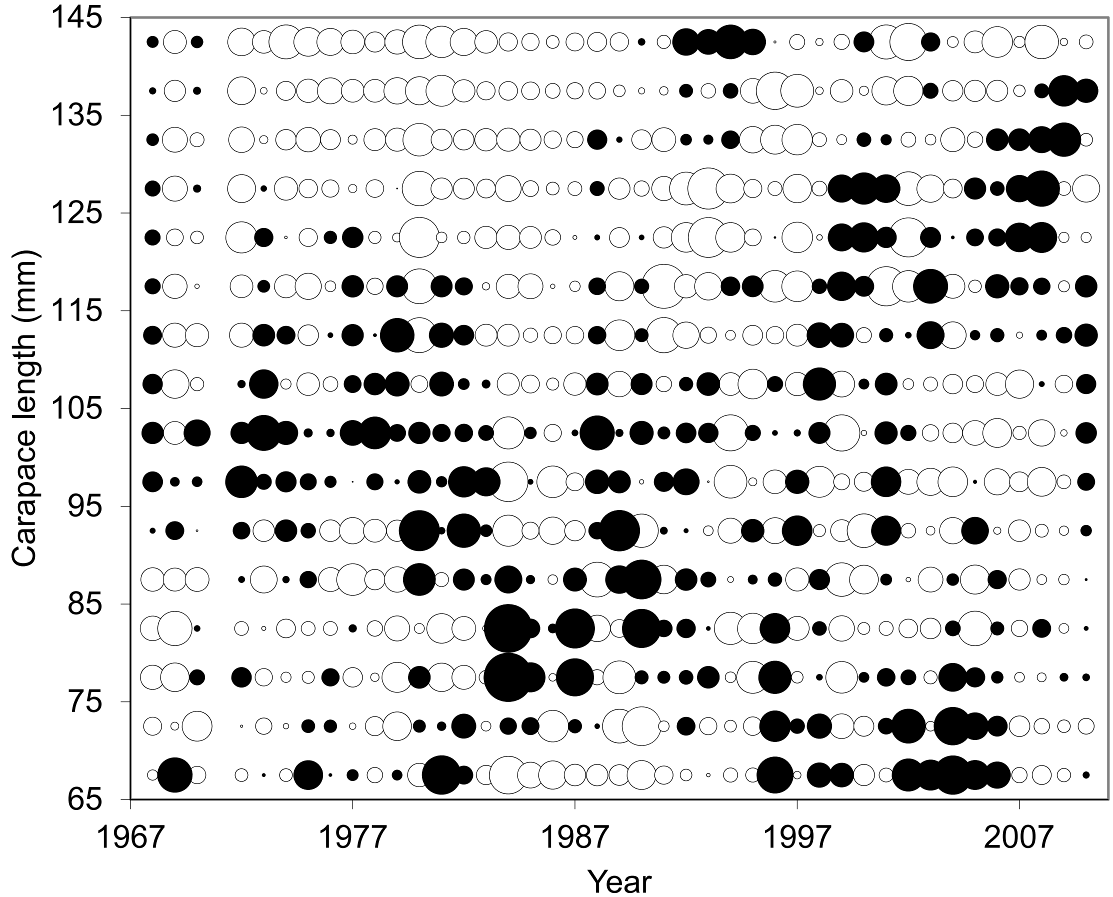


Figure 27(2). Standardized residuals of proportions of survey female red king crabs (1968-2010) under scenario 2. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

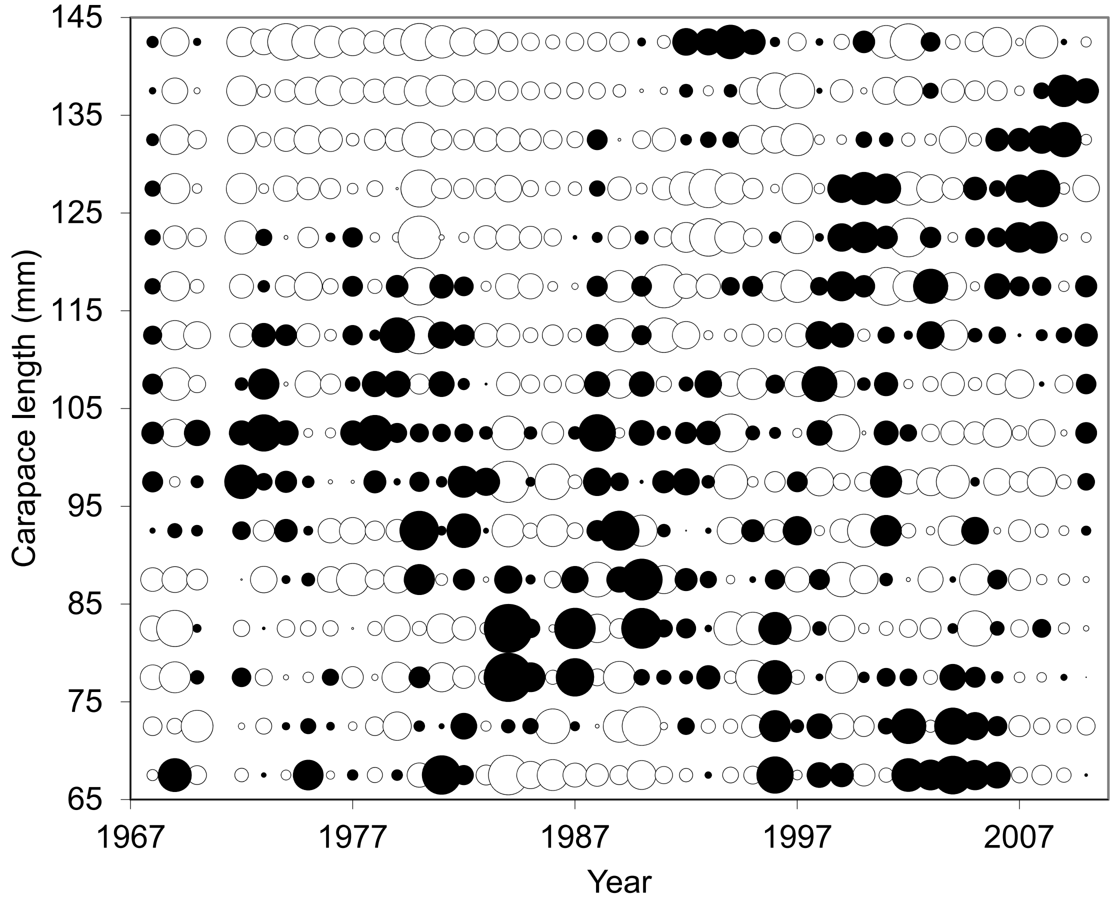


Figure 27(3). Standardized residuals of proportions of survey female red king crabs (1968-2010) under scenario 3. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

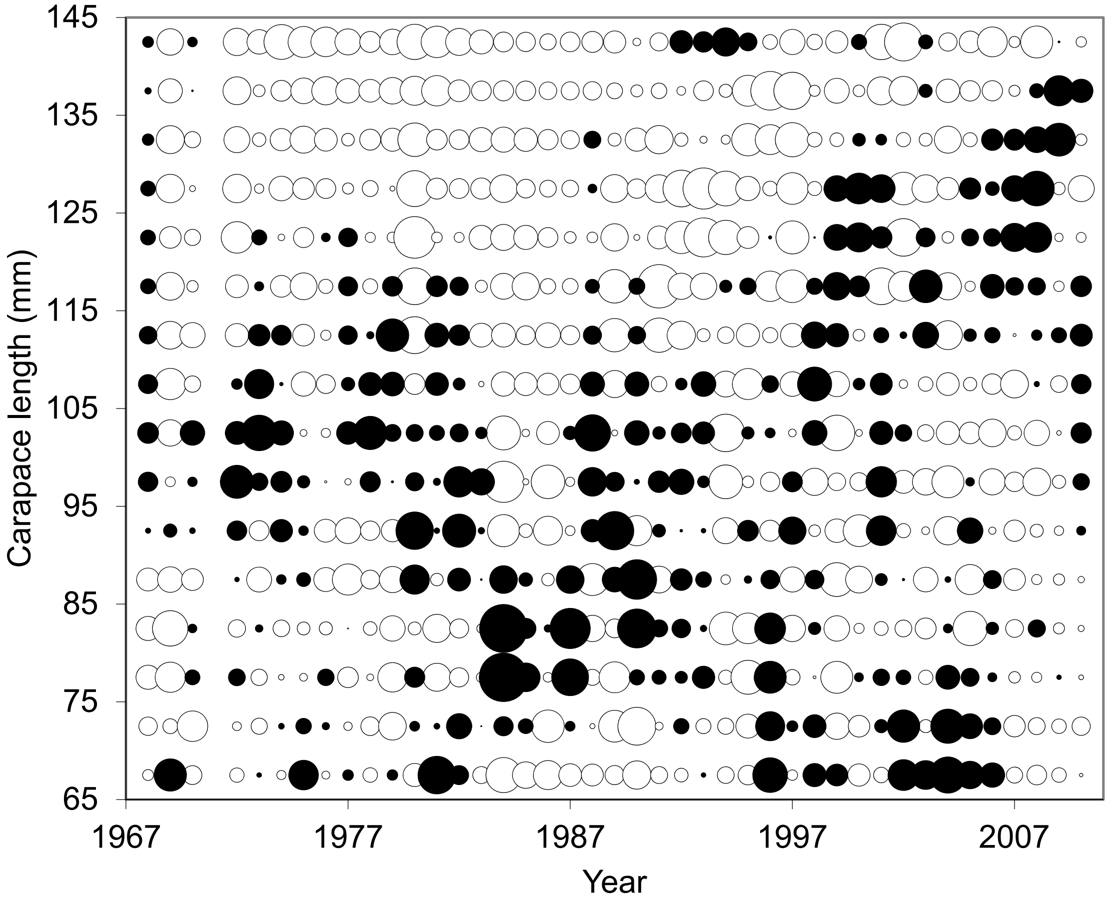


Figure 27(4). Standardized residuals of proportions of survey female red king crabs (1968-2010) under scenario 4. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

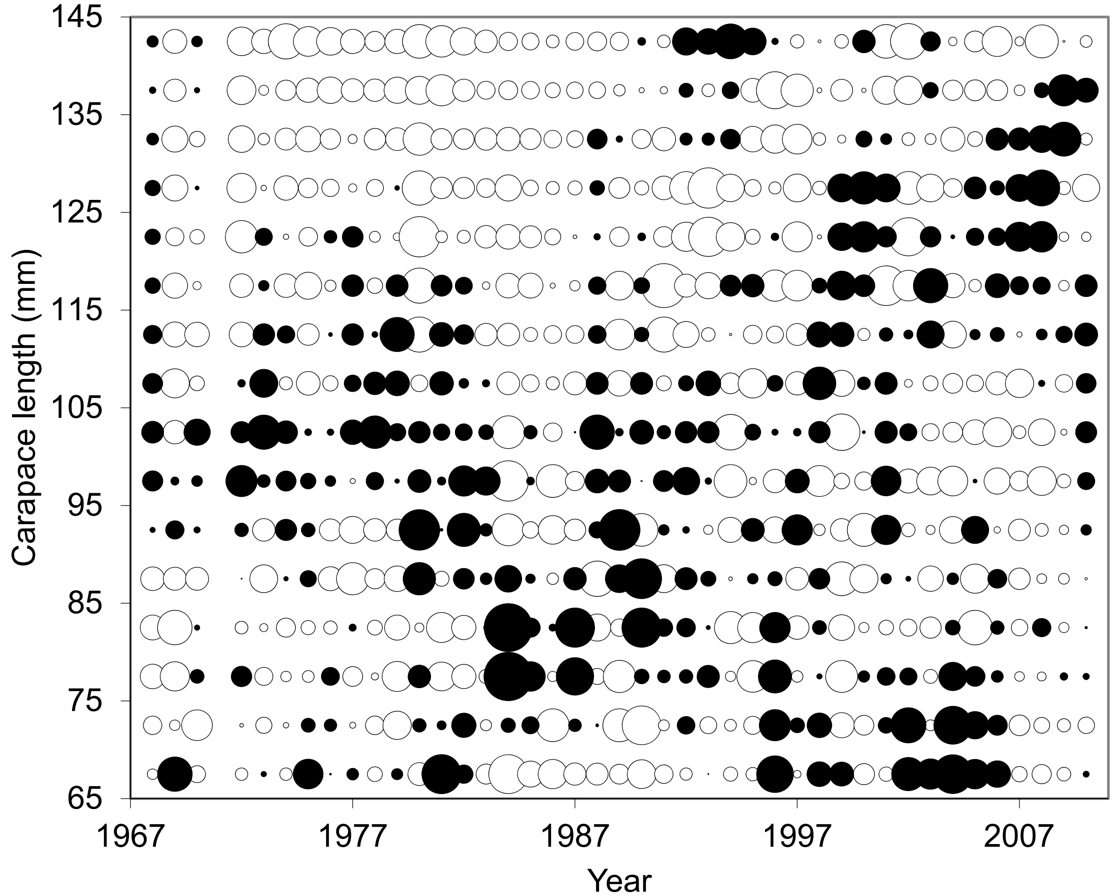


Figure 27(5). Standardized residuals of proportions of survey female red king crabs (1968-2010) under scenario 5. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

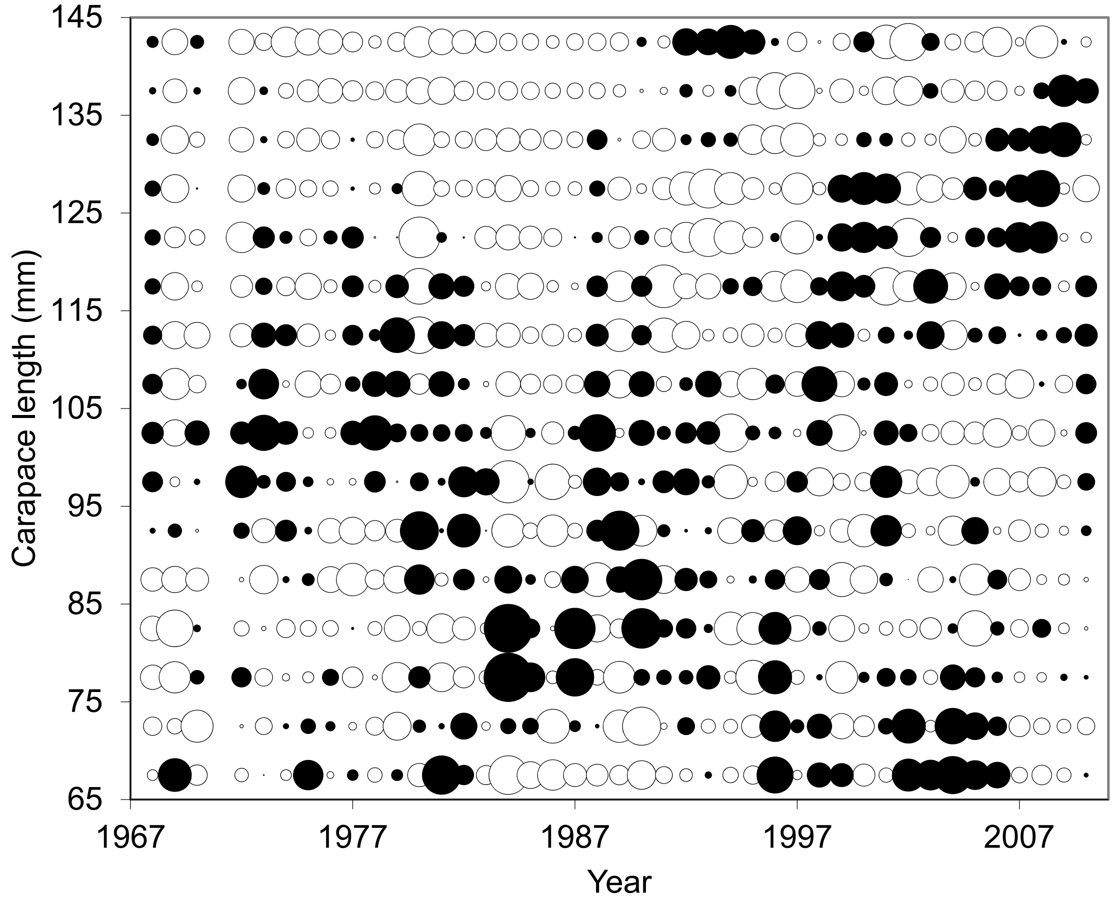


Figure 27(6). Standardized residuals of proportions of survey female red king crabs (1968-2010) under scenario 6. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

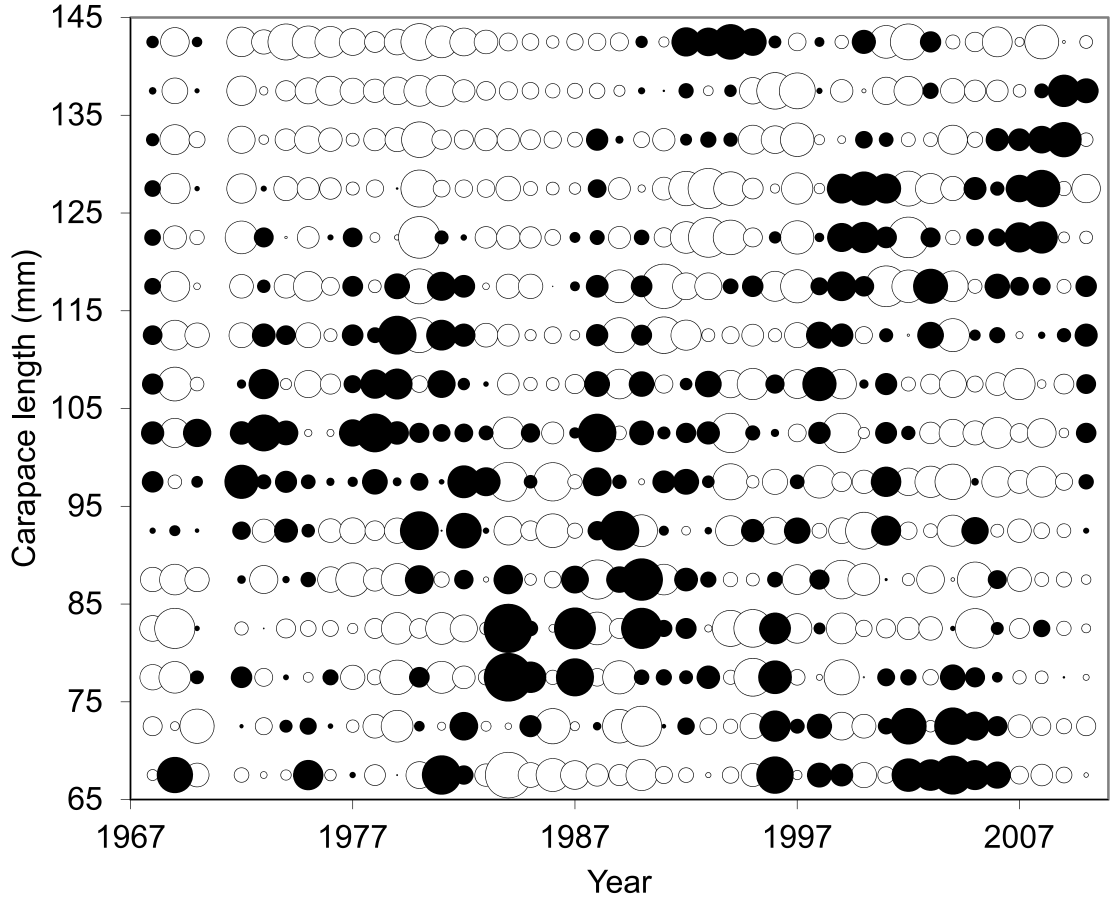


Figure 27(7). Standardized residuals of proportions of survey female red king crabs (1968-2010) under scenario 7. Solid circles are positive residuals, and open circles are negative residuals. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

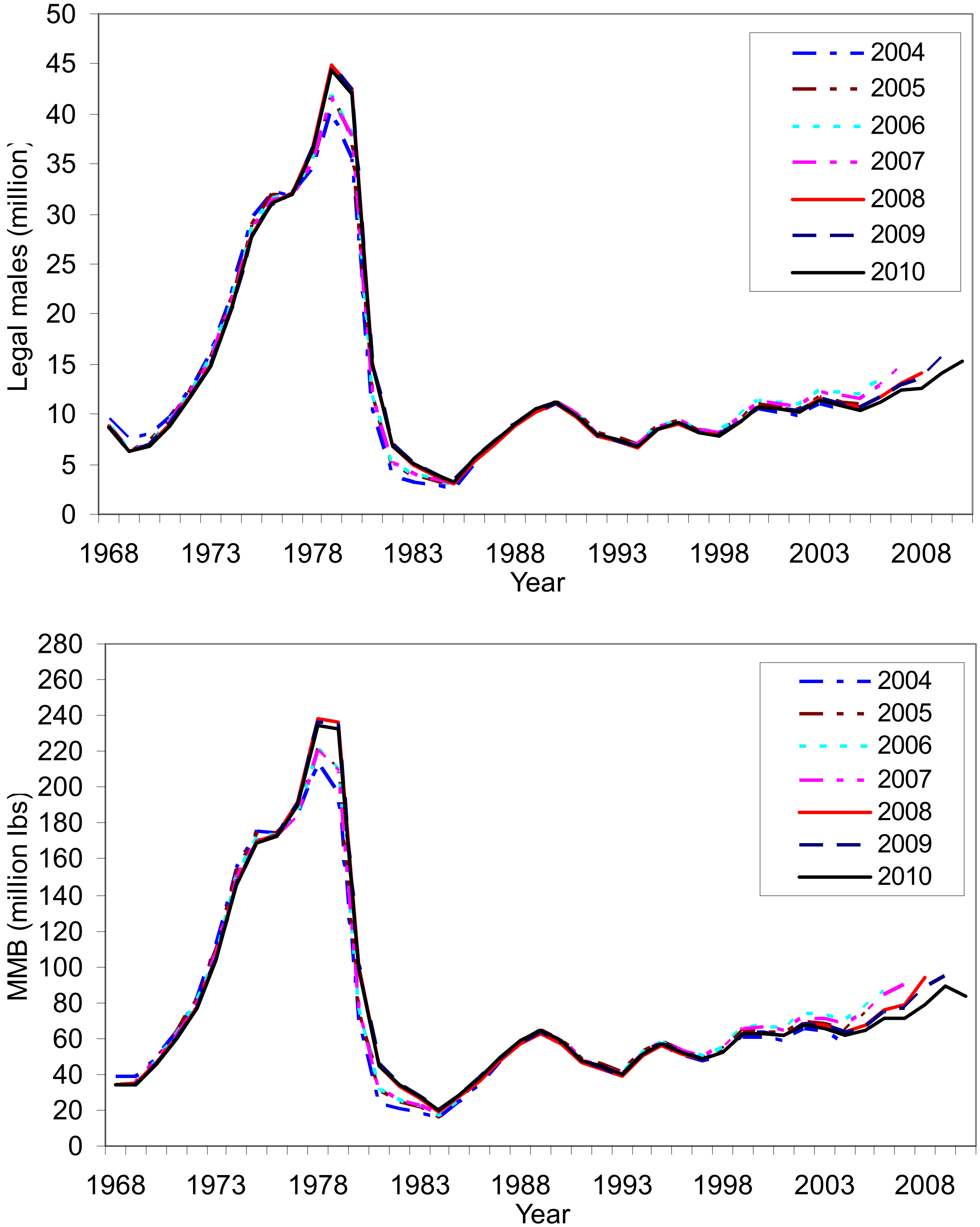
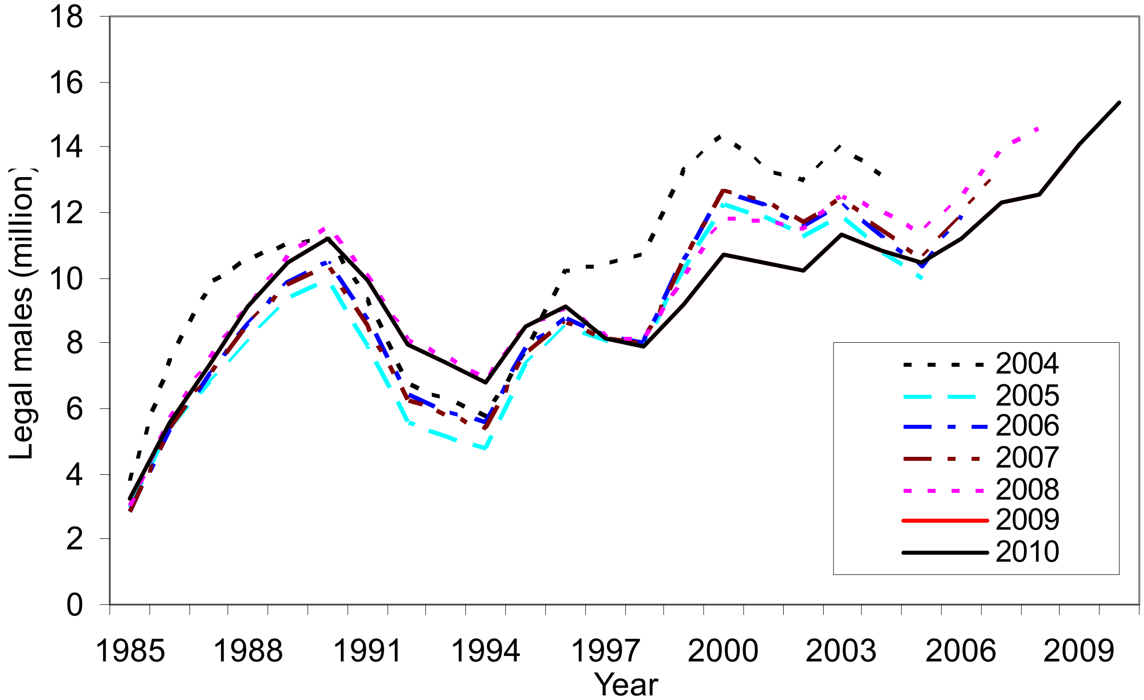


Figure 28(0). Comparison of estimates of legal male abundance (top) and mature male biomass (bottom) on Feb. 15 of Bristol Bay red king crab from 1968 to 2010 made with terminal years 2004-2010 with scenario 0. These are results of the 2010 model. Legend shows the year in which the assessment was conducted. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.



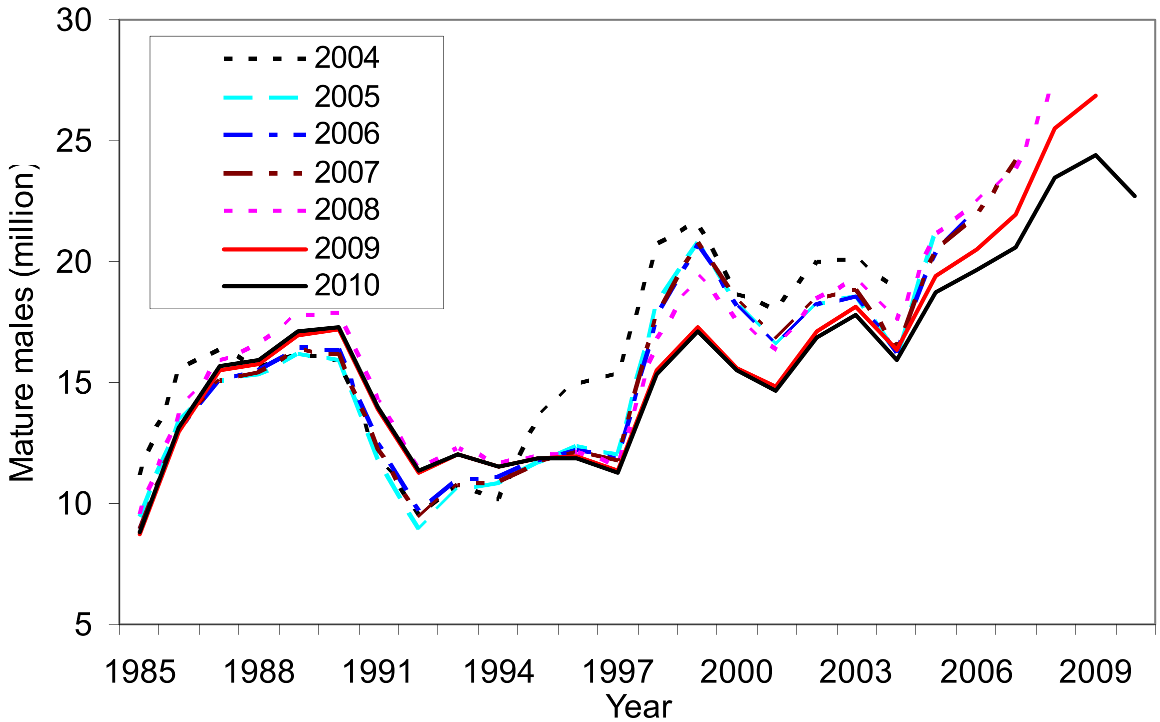


Figure 29(0). Comparison of estimates of legal male abundance (top) and mature males (bottom) of Bristol Bay red king crab from 1985 to 2010 made with terminal years 2004-2010 with scenario 0. These are results of historical assessments. Legend shows the year in which the assessment was conducted. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

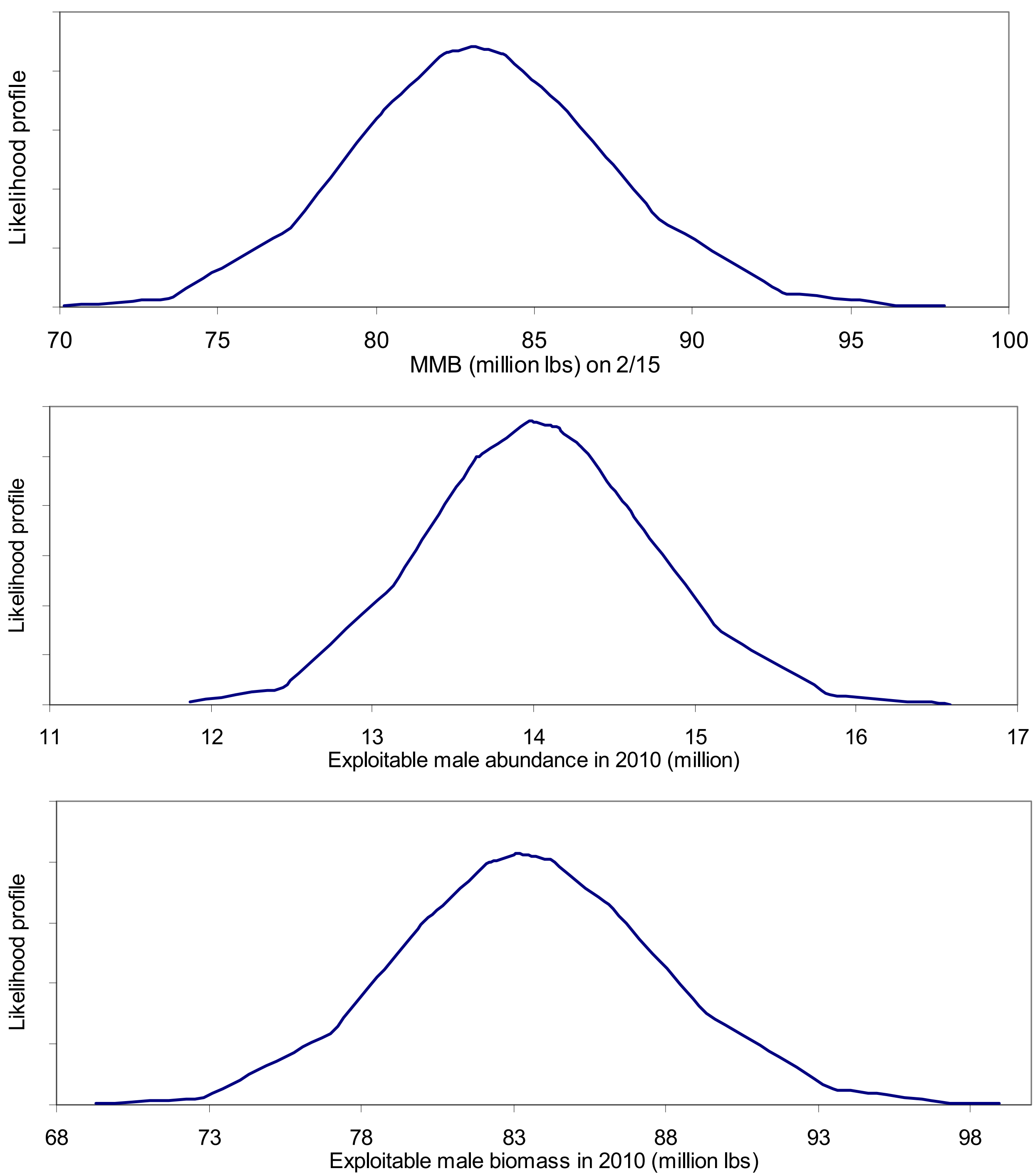


Figure 30(0). Likelihood profiles for estimated mature male biomass on Feb. 15 and exploitable male abundance and biomass at the fishing time for the 2010 season with $F_{35\%}$ under scenario 0. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

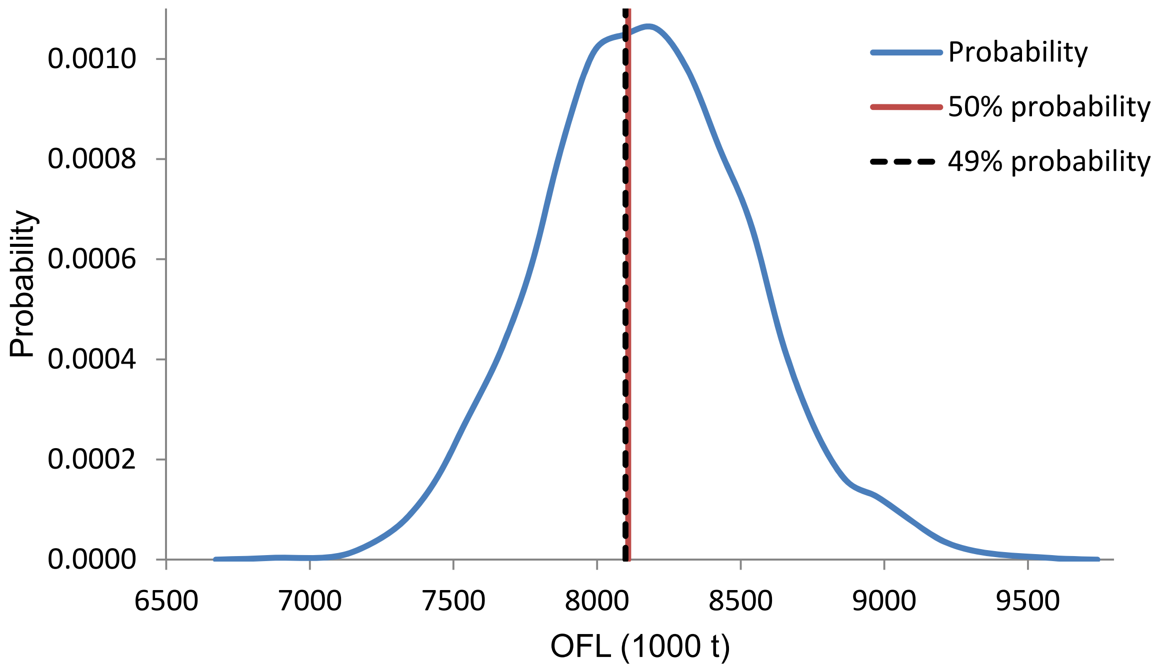


Figure 31(7). The 2010 OFL distributions with scenario 7. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively.

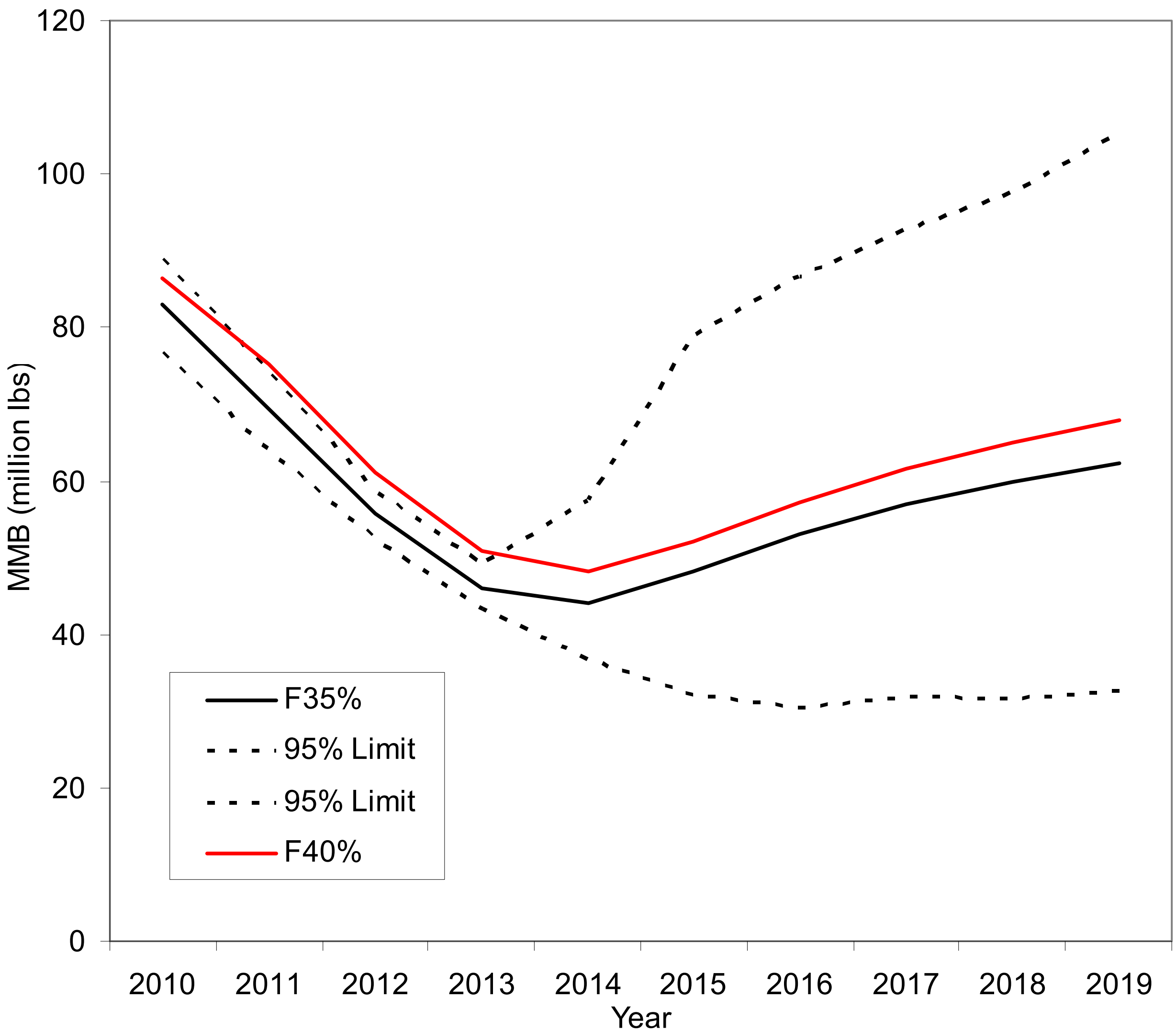


Figure 32(0). Projected mature male biomass on Feb. 15 with $F_{40\%}$, and $F_{35\%}$ harvest strategy with $F_{35\%}$ constraint during 2010-2119. Input parameter estimates are based on scenario 0. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the confidence limits are for the $F_{35\%}$ harvest strategy.

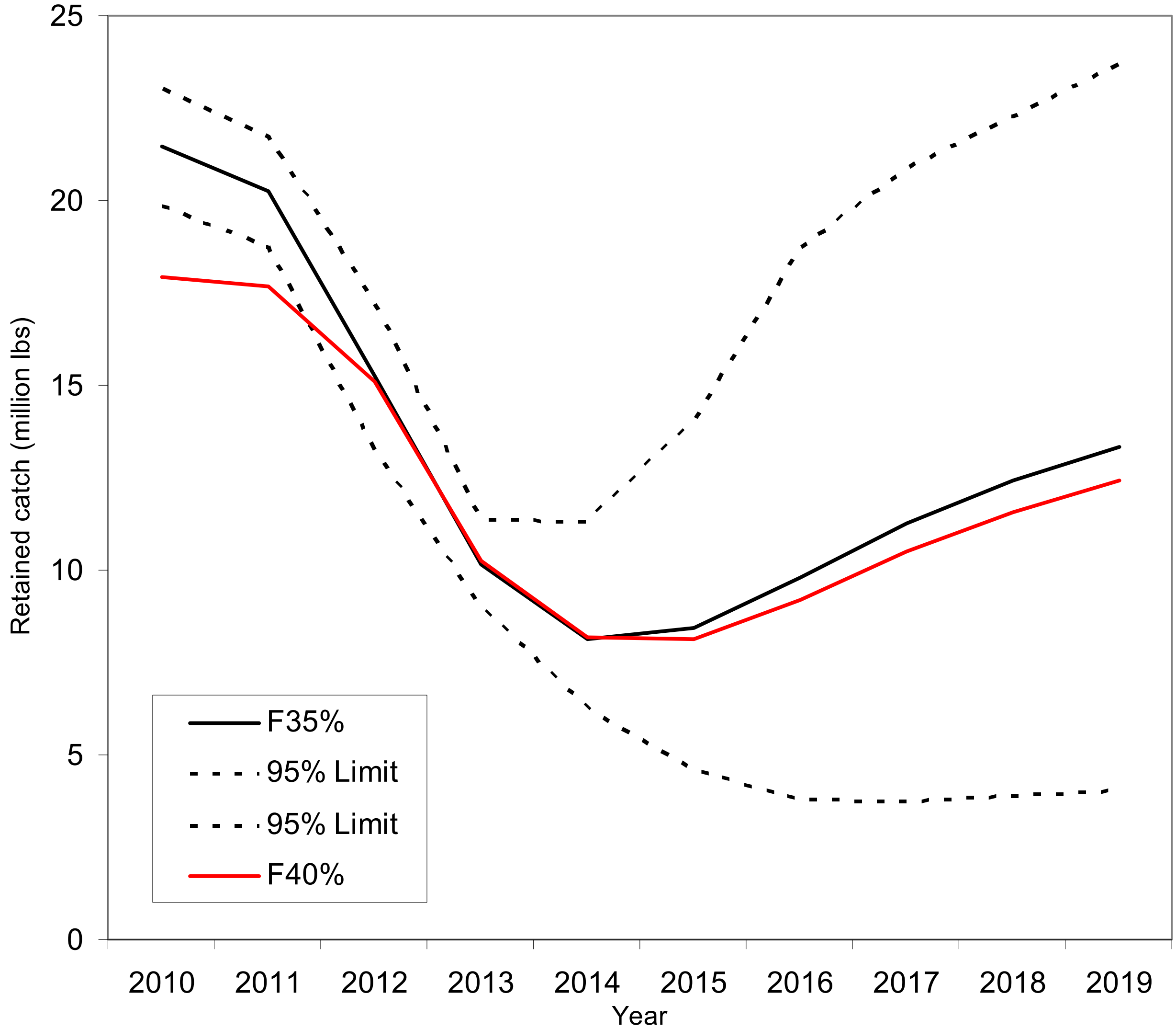


Figure 33(0). Projected retained catch biomass with $F_{40\%}$, and $F_{35\%}$ harvest strategy with $F_{35\%}$ constraint during 2010-2119. Input parameter estimates are based on scenario 0. Pot and trawl handling mortality rates were assumed to be 0.2 and 0.8, respectively, and the confidence limits are for the $F_{35\%}$ harvest strategy.

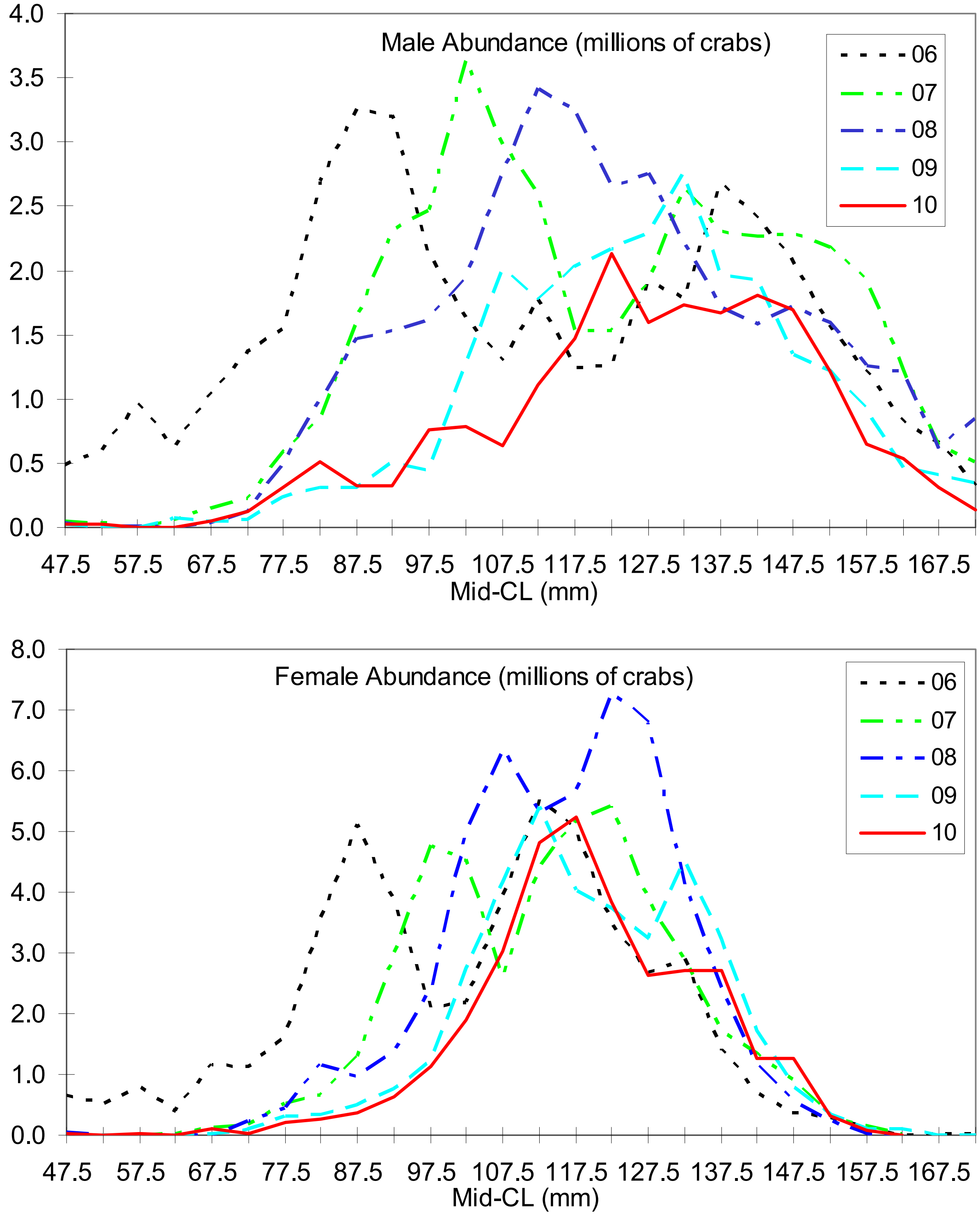


Figure 34. Length frequency distributions of male (top panel) and female (bottom panel) red king crabs in Bristol Bay from NMFS trawl surveys during 2006-2010. For purposes of these graphs, abundance estimates are based on area-swept methods.

Appendix A. Description of the Bristol Bay Red King Crab Model

a. Model Description

i. Population model

The original LBA model was described in detail by Zheng et al. (1995a, 1995b) and Zheng and Kruse (2002). Male crab abundances by carapace length and shell condition in any one year are modeled to result from abundances in the previous year minus catch and handling and natural mortalities, plus recruitment, and additions to or losses from each length class due to growth:

$$
\begin{aligned}
N_{l+1,t+1} &= \sum_{l'=1}^{l'=l+1} \{P_{l',l+1}\,[(N_{l',t}+O_{l',t})\,e^{-M_t} - (C_{l',t}+D_{l',t})\,e^{(y_t-1)M_t} - T_{l,t}\mathrm{e}^{(j_t-1)M_t}]\,m_{l'}\} + R_{l+1,t+1}\,, \\
O_{l+1,t+1} &= [(N_{l+1,t}+O_{l+1,t})\,e^{-M_t} - (C_{l+1,t}+D_{l+1,t})\,e^{(y_t-1)M_t} - T_{l+1,t}\mathrm{e}^{(j_t-1)M_t}]\,(1-m_{l+1}),
\end{aligned}
\tag{1}
$$

where

$N_{l,t}$ is newshell crab abundance in length class l and year t,

$O_{l,t}$ is oldshell crab abundances in length class l and year t,

M is the instantaneous natural mortality,

m_l is the molting probability for length class l,

$R_{l,t}$ is recruitment into length class l in year t,

y_t is the lag in years between the assessment survey and the mid fishery time in year t,

j_t is the lag in years between the assessment survey and the mid Tanner crab fishery time in year t,

$P_{l',l}$ is the proportion of molting crabs growing from length class l' to l after one molt,

$C_{l,t}$ is the retained catch of length class l in year t, and

$D_{l,t}$ is the discarded mortality catch of length class l in year t, including directed pot and trawl bycatch,

$T_{l,t}$ is the discarded mortality catch of length class l in year t from the Tanner crab fishery.

The minimum carapace length for males is set at 65 mm, and crab abundance is modeled with a length-class interval of 5 mm. The last length class includes all crabs ≥160-mm CL. There are 20 length classes/groups. $P_{l',l}$, m_l, $R_{l,t}$, $C_{l,t}$, and $D_{l,t}$ are computed as follows:

Mean growth increment per molt is assumed to be a linear function of pre-molt length:

$$G_l = a + b\,\iota, \tag{2}$$

where a and b are constants. Growth increment per molt is assumed to follow a gamma distribution:

$$g(x \mid \alpha_l, \beta) = x^{\alpha_l - 1}\ e^{-x/\beta} / [\beta^{\alpha_l}\ \Gamma(\alpha_l)]. \tag{3}$$

The expected proportion of molting individuals growing from length class l_1 to length class l_2 after one molt is equal to the sum of probabilities within length range $[\iota_1, \iota_2)$ of the receiving length class l_2 at the beginning of the next year:

$$P_{l_1,l_2} = \int_{\iota_1 - \iota}^{\iota_2 - \iota} g(x \mid \alpha_l, \beta) dx, \tag{4}$$

where ι is the mid-length of length class l_1. For the last length class L, $P_{L,L} = 1$.

The molting probability for a given length class l is modeled by an inverse logistic function:

$$m_l = 1 - \frac{1}{1 + e^{-\beta\ (l - L_{50})}}, \tag{5}$$

where

β, L_{50} are parameters, and

ι is the mid-length of length class l.

Recruitment is defined as recruitment to the model and survey gear rather than recruitment to the fishery. Recruitment is separated into a time-dependent variable, R_t, and size-dependent variables, U_l, representing the proportion of recruits belonging to each length class. R_t was assumed to consist of crabs at the recruiting age with different lengths and thus represents year class strength for year t. $R_{l,t}$ is computed as

$$R_{l,t} = R_t U_l, \tag{6}$$

where U_l is described by a gamma distribution similar to equations (3) and (4) with a set of parameters α_r and β_r. Because of different growth rates, recruitment was estimated separately for males and females under a constraint of approximately equal sex ratios of recruitment over time.

Before 1990, no observed bycatch data were available in the directed pot fishery; the crabs that were discarded and died in those years were estimated as the product of handling mortality rate, legal harvest rates, and mean length-specific selectivities. It is difficult to estimate bycatch from the Tanner crab fishery before 1991. A reasonable index to estimate bycatch fishing mortalities is potlifts of the Tanner crab fishery within the distribution area of Bristol Bay red king crab. Thus, bycatch fishing mortalities from the Tanner crab fishery before 1991 were estimated to be proportional to the smoothing average of potlifts east of 163° W. The smoothing average is equal to $(P_{t-2}+2P_{t-1}+3P_t)/6$ for the potlift in year t. The smoothing process not only smoothes the annual number of potlifts, it also indexes the effects of lost pots during the previous years. For bycatch, all fishery catch and discard mortality bycatch are estimated as:

$$C_{l,t}\ or\ D_{l,t} = (N_{l,t} + O_{l,t})\ e^{-y_t M_t} (1 - e^{-s_l F_t}) \tag{7}$$

where

s_l is selectivity for retained, pot or trawl discarded mortality catch of length class l, and

F_t is full fishing mortality of retained, pot or trawl discarded mortality catch in year t.

For discarded mortality bycatch from the Tanner crab fishery, y_t is replaced by j_t in the right side of equation (7).

The female crab model is the same as the male crab model except that the retained catch equals zero and molting probability equals 1.0 to reflect annual molting (Powell 1967). The minimum carapace length for females is set at 65 mm, and the last length class includes all crabs ≥140-mm CL, resulting in length groups 1-16. Three sets of growth increments per molt are used for females due to changes in sizes at maturity over time (Figures A2 and A3).

ii. Fisheries Selectivities

Retained selectivity, female pot bycatch selectivity, and both male and female trawl bycatch selectivity are estimated as a function of length:

$$s_l = \frac{1}{1+e^{-\beta\ (l-L_{50})}}, \tag{8}$$

Different sets of parameters (β, L_{50}) are estimated for retained males, female pot bycatch, male and female trawl bycatch, and discarded males and females from the Tanner crab fishery. Because some catches were from the foreign fisheries during 1968-1972, a different set of parameters (β, L_{50}) are estimated for retained males for this period and a third parameter, sel_62.5mm, is used to explain the high proportion of catches in the last length group.

Male pot bycatch selectivity is modeled by two linear functions:

$$\begin{aligned} s_l &= \varphi + \kappa\, l, \quad if\ l < 135\,\text{mm CL}, \\ s_l &= s_{l-1} + 5\gamma, \quad if\ l > 134\,\text{mm CL} \end{aligned} \tag{9}$$

Where

φ, κ, γ are parameters.

During 2005-2008, a portion of legal males were also discarded in the pot fishery. The selectivity for this high grading was estimated to be the retained selectivity in each year times a high grading parameter, hg_t.

iii. Trawl Survey Selectivities/Catchability

Trawl survey selectivities/catchability are estimated as

$$s_l = \frac{Q}{1+e^{-\beta\ (l-L_{50})}}, \tag{10}$$

with different sets of parameters (β, L_{50}) estimated for males and females as well as four different periods (1968-69, 1970-72, 1973-81 and 1982-09). Survey selectivity for the first length group (67.5 mm) was assumed to be the same for both males and females, so only three parameters (β, L_{50} for females and L_{50} for males) were estimated in the model for each of the four periods. Parameter Q was called the survey catchability that was estimated based on a trawl experiment by Weinberg et al. (2004, Figure A1). Q was assumed to be constant over time except during 1970-1972 when the survey catchability was small.

Assuming that the BSFRF survey caught all crabs within the area-swept, the ratio between NMFS abundance and BSFRF abundance is a capture probability for the NMFS survey net. The Delta method was used to estimate the variance for the capture probability. A maximum likelihood method was used to estimate parameters for a logistic function as an estimated capture probability curve (Figure A1). For a given size, the estimated capture probability is smaller based on the BSFRF survey than from the trawl experiment, but the *Q* value is similar between the trawl experiment and the BSFRF surveys (Figure A1). Because many small-sized crabs are in the shallow water areas that are not accessible for the trawl survey, NMFS survey catchability/selectivity consists of capture probability and crab availability.

b. Software Used: AD Model Builder (Otter Research Ltd. 1994).

c. Likelihood Components

A maximum likelihood approach was used to estimate parameters. For length compositions ($p_{l,t,s,sh}$), the likelihood functions are :

$$Rf=\prod_{l=1}^{L}\prod_{t=1}^{T}\prod_{s=1}^{2}\prod_{sh=1}^{2}\frac{\left\{\exp\left[-\frac{(p_{l,t,s,sh}-\hat{p}_{l,t,s,sh})^2}{2\sigma^2}\right]+0.01\right\}}{\sqrt{2\pi\sigma^2}}, \tag{11}$$

$$\sigma^2=\left[\hat{p}_{l,t,s,sh}(1-\hat{p}_{l,t,s,sh})+0.1/L\right]/n,$$

where

L is the number of length groups,

T is the number of years, and

n is the effective sample size, which was assumed to be 400 for retained males, 200 for trawl survey, 100 for pot male and Tanner crab fisheries bycatch, and 50 for trawl and pot female bycatch length composition data.

The weighted negative log-likelihood functions are:

$$\begin{aligned}
&\textit{Length compositions}: \quad -\sum \ln(Rf_i)\,,\\
&\textit{Biomasses other than survey}: \quad \lambda_j\sum\left[\ln(C_t/\hat{C}_t)^2\right],\\
&\textit{NMFS survey biomass}: \quad \sum\left[\ln(B_t/\hat{B}_t)^2/(2\ln(CV_t^2+1))\right],\\
&\textit{BSFRF mature males}: \quad \sum[\ln(N_t/\hat{N}_t)^2/(2\ln(CV_t^2+1))],\\
&\textit{R variation}: \quad \lambda_R\sum[\ln(R_t/\overline{R})^2]\,,\\
&\textit{R sex ratio}: \quad \lambda_s[\ln(\overline{R}_M/\overline{R}_F)^2]\,,
\end{aligned} \tag{12}$$

Where

R_t is the recruitment in year t,

$\overline{R}$ is the mean recruitment,

$\overline{R}_M$ is the mean male recruitment,

$\overline{R}_F$ is the mean female recruitment.

Weights λ_j are assumed to be 500 for retained catch biomass, and 100 for all bycatch biomasses, 2 for recruitment variation, and 10 for recruitment sex ratio. These λ_j values represent prior assumptions about the accuracy of the observed catch biomass data and about the variances of these random variables.

d. Population State in Year 1.

To increase the efficiency of the parameter-estimation algorithm, we assumed that the smoothed relative frequencies of length and shell classes from survey year 1968 approximate the true relative frequencies within sexes. Thus, only total abundances of males and females for the first year were estimated; 3n unknown parameters for the abundances in the first year, where n is the number of length-classes, were reduced to one under this assumption.

e. Parameter estimation framework:

i. Parameters estimated independently

Basic natural mortality, length-weight relationships, and mean growth increments per molt were estimated independently outside of the model. Mean length of recruits to the model depends on growth and was assumed to be 72.5 for both males and females. High grading parameters hg_t were estimated to be 0.2785 in 2005, 0.0440 in 2006, 0.0197 in 2007, and 0.0198 in 2008 based on the proportions of discarded legal males to total caught legal males. Handling mortality rates were set to 0.2 for the directed pot fishery, 0.25 for the Tanner crab fishery, and 0.8 for the trawl fisheries.

(1). Natural Mortality

Based on an assumed maximum age of 25 years and the 1% rule (Zheng 2005), basic M was estimated to be 0.18 for both males and females. Natural mortality in a given year, M_t, equals to $M + Mm_t$ (for males) or $M + Mf_t$ (females). One value of Mm_t during 1980-1985 was estimated and two values of Mf_t during 1980-1984 and 1976-79, 1985-93 were estimated in the model.

(2). Length-weight Relationship

Length-weight relationships for males and females were as follows:

$$
\begin{aligned}
&\text{Immature Females:} \quad W = 0.010271\, L^{2.388},\\
&\text{Ovigerous Females:} \quad W = 0.02286\, L^{2.234}, \qquad (13)\\
&\text{Males:} \quad W = 0.000361\, L^{3.16},
\end{aligned}
$$

where

W is weight in grams, and
L is CL in mm.

(3). Growth Increment per Molt

A variety of data are available to estimate male mean growth increment per molt for Bristol Bay RKC. Tagging studies were conducted during the 1950s, 1960s and 1990s, and mean growth increment per molt data from these tagging studies in the 1950s and 1960s were analyzed by Weber and Miyahara (1962) and Balsiger (1974). Modal analyses were conducted for the data during 1957-1961 and the 1990s (Weber 1967; Loher et al. 2001). Mean growth increment per molt may be a function of body size and shell condition and vary over time (Balsiger 1974; McCaughran and Powell 1977); however, for simplicity, mean growth increment per molt was assumed to be only a function of body size in the models. Tagging data were used to estimate mean growth increment per molt as a function of pre-molt length for males (Figure A2). The results from modal analyses of 1957-1961 and the 1990s were used to estimate mean growth increment per molt for immature females during 1968-1993 and 1994-2008, respectively, and the data presented in Gray (1963) were used to estimate those for mature females (Figure A2). To make a smooth transition of growth increment per molt from immature to mature females, weighted growth increment averages of 70% and 30% at 92.5 mm CL pre-molt length and 90% and 10% at 97.5 mm CL were used, respectively, for mature and immature females during 1983-1993. These percentages are roughly close to the composition of maturity. During 1968-1982, females matured at a smaller size, so the growth increment per molt as a function of length was shifted to smaller increments. Likewise, during 1994-2008, females matured at a slightly higher size, so the growth increment per molt was shifted to high increments for immature crabs (Figure A2). Once mature, the growth increment per molt for male crabs decreases slightly and annual molting probability decreases, whereas the growth increment for female crabs decreases dramatically but annual molting probability remains constant at 1.0 (Powell 1967).

(4). Sizes at Maturity for Females

NMFS collected female reproductive condition data during the summer trawl surveys. Mature females are separated from immature females by a presence of egg clutches or egg cases. Proportions of mature females at 5-mm length intervals were summarized and a logistic curve was fitted to the data each year to estimate sizes at 50% maturity. Sizes at 50% maturity are illustrated in Figure A3 with mean values for three different periods (1975-82, 1983-93 and 1994-08).

(5). Sizes at Maturity for Males

Sizes at functional maturity for Bristol Bay male RKC have been assumed to be 120 mm CL (Schmidt and Pengilly 1990). This is based on mating pair data collected off Kodiak Island (Figure A4). Sizes at maturity for Bristol Bay female RKC are about 90 mm CL, about 15 mm CL less than Kodiak female RKC (Pengilly et al. 2002). The size ratio of mature males to females is 1.3333 at sizes at maturity for Bristol Bay RKC, and since mature males grow at much larger increments than mature females, the mean size ratio of mature males to females is most likely larger than this ratio. Size ratios of the large majority of Kodiak mating pairs were less than 1.3333, and in some bays, only a small proportion of mating pairs had size ratios above 1.3333 (Figure A4).

In the laboratory, male RKC as small as 80 mm CL from Kodiak and SE Alaska can successfully mate with females (Paul and Paul 1990). But few males less than 100 mm CL were observed to mate with females in the wild. Based on the size ratios of males to females in the Kodiak mating pair data, setting 120 mm CL as a minimum size of functional maturity for Bristol Bay male RKC is proper in terms of managing the fishery.

(6) Potential Reasons for High Mortality during the Early 1980s

Bristol Bay red king crab abundance had declined sharply during the early 1980s. Many factors have been speculated for this decline: (i) completely wiped out by fishing: directed pot fishery, other directed pot fishery (Tanner crab fishery), and bottom trawling; and (ii) high fishing and natural mortality. With the survey abundance, harvest rates in 1980 and 1981 were among the highest, thus the directed fishing definitely had a big impact on the stock decline, especially legal and mature males. However, for the sharp decline during 1980-1884 for males, 3 out of 5 years had low mature harvest rates. During 1981-1984 for females, 3 out of 4 years had low mature harvest rates. Also pot catchability for females and immature males are generally much lower than for legal males, so the directed pot fishing alone cannot explain the sharp decline for all segments of the stock during the early 1980s.

Red king crab bycatch in the eastern Bering Sea Tanner crab fishery is another potential factor. The main overlap between Tanner crab and Bristol Bay red king crab is east of 163^{o} W. No absolute red king crab bycatch estimates are available until 1991. So there are insufficient data to fully evaluate the impact. Retained catch and potlifts from the eastern Bering Sea Tanner crab fishery are illustrated in Figure A5. The observed red king crab bycatch in the Tanner crab fishery during 1991-1993 and total potlifts east of 163^{o} W during 1968 to 2005 were used to estimate the bycatch mortality in the current model. Because winter sea surface temperatures and air temperatures were warmer (which means a lower handling mortality rate) and there were fewer potlifts during the early 1980s than during the early 1990s, bycatch in the Tanner crab fishery is unlikely to have been a main factor for the sharp decline of Bristol Bay red king crab.

Several factors may have caused increases in natural mortality. Crab diseases in the early 1980s were documented by Sparks and Morado (1985), but inadequate data were collected to examine their effects on the stock. Stevens (1990) speculated that senescence may be a factor because many crabs in the early 1980s were very old due to low temperatures in the 1960s and early 1970s. The biomass of the main crab predator, Pacific cod, increased about 10 times during the late 1970s and early 1980s. Yellowfin sole biomass also increased substantially during this period. Predation is primarily on juvenile and molting/softshell crabs. But we lack stomach samples in shallow waters (juvenile habitat) and during the period when red king crabs molt. Also cannibalism occurs during molting periods for red king crabs. High crab abundance in the late 1970s and early 1980s may have increased the occurrence of cannibalism.

Overall, the likely causes for the sharp decline in the early 1980s are combinations of the above factors, such as pot fisheries on legal males, bycatch and predation on females and juvenile and sublegal males, senescence for older crabs, and disease for all crabs. In our model, we estimated one mortality parameter for males and another for females during 1980-1984. We also estimated a mortality parameter for females during 1976-1979 and 1985-1993. These three mortality parameters are additional to the basic natural mortality of 0.18, all directed fishing mortality and non-directed fishing mortality. These three mortality parameters could be attributed to natural mortality as well as undocumented non-directed fishing mortality. The model fit the data much better with these three parameters than without them.

ii. Parameters estimated conditionally

The following model parameters were estimated for male and female crabs: total recruits for each year (year class strength R_t for t = 1969 to 2009), total abundance in the first year (1968), growth parameter β and recruitment parameter β_r for males and females separately. Molting probability parameters β and L_{50} were also estimated for male crabs. Estimated parameters also include β and L_{50} for retained selectivity, β and L_{50} for pot-discarded female selectivity, β and L_{50} for pot-discarded male and female selectivities from the eastern Bering Sea Tanner crab fishery, β and L_{50} for groundfish trawl discarded selectivity, φ, κ and γ for pot-discarded male selectivity, and β for trawl survey selectivity and L_{50} for trawl survey male and females separately. NMFS survey catchabilities Q for 1968-69 and 1973-2009 and Q_m (for males) and Q_f (for females) for 1970-72 were also estimated. Annual fishing mortalities were also estimated for the directed pot fishery for males (1968-2008), pot-discarded females from the directed fishery (1990-2008), pot-discarded males and females from the eastern Bering Sea Tanner crab fishery (1991-93), and groundfish trawl discarded males and females (1976-2008). Three additional mortality parameters for Mm_t and Mf_t were also estimated. The total number of parameters to be estimated was 223. Some estimated parameters were constrained in the model. For example, male and female recruitment estimates were forced to be close to each other for a given year.

f. Definition of model outputs.

i. Biomass: two population biomass measurements are used in this report: total survey biomass (crabs >64 mm CL) and mature male biomass (males >119 mm CL). Mating time is assumed to Feb. 15.

ii. Recruitment: new number of males in the 1st seven length classes (65- 99 mm CL) and new number of females in the 1st five length classes (65-89 mm CL).

iii. Fishing mortality: full-selected instantaneous fishing mortality rate at the time of fishery.

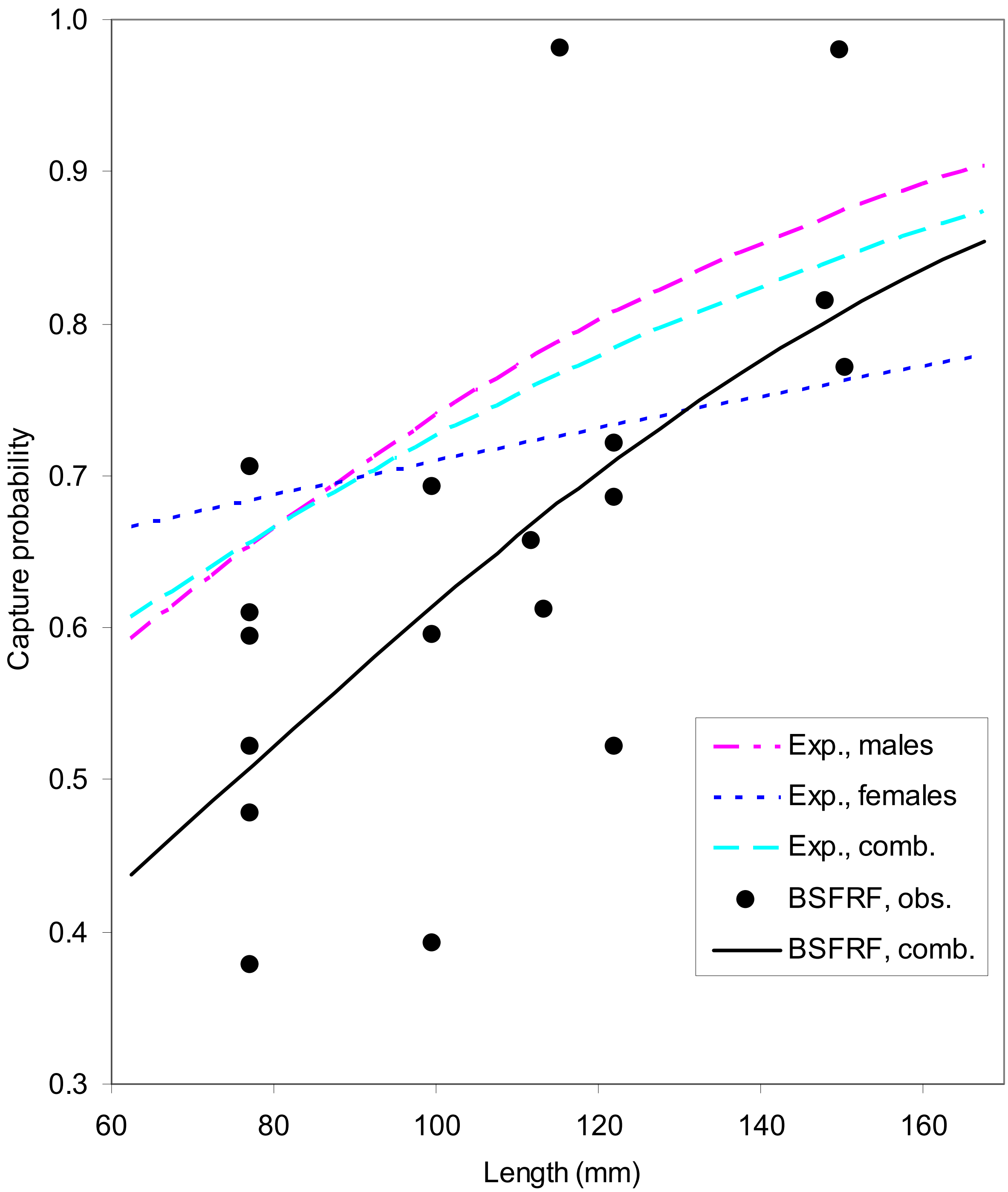
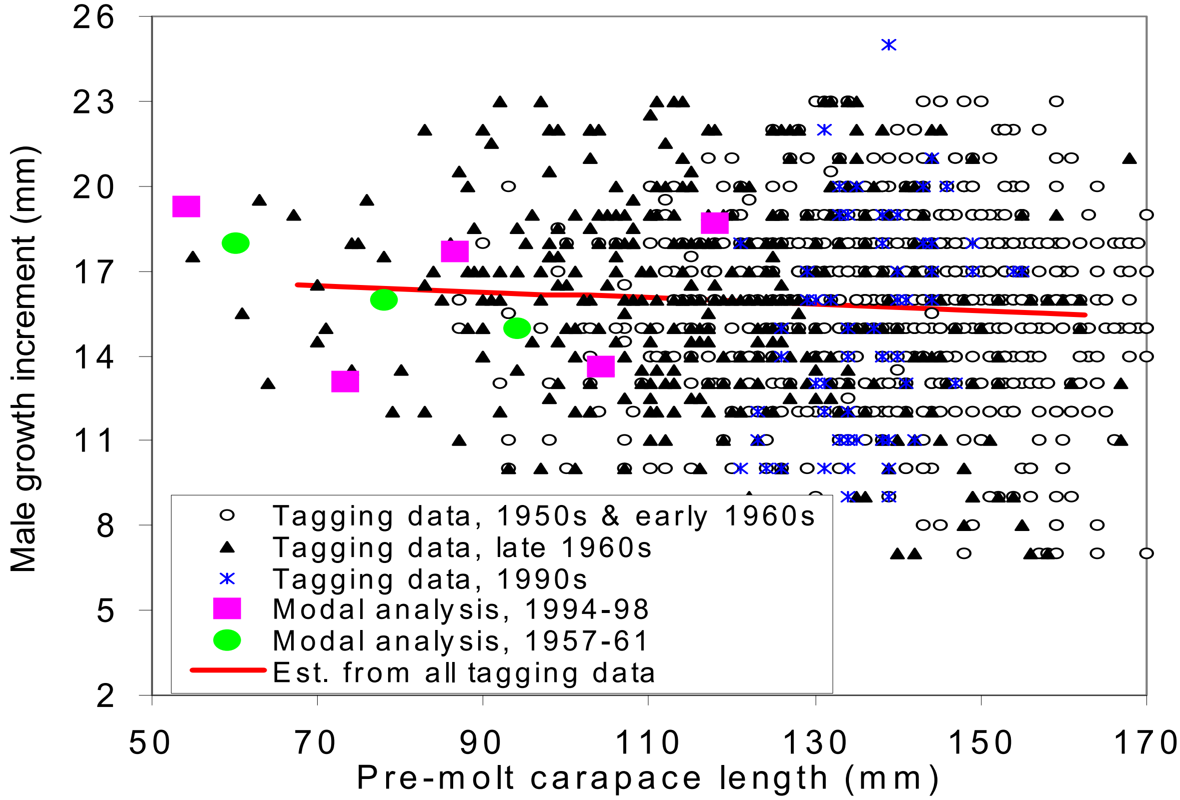


Figure A1. Estimated capture probabilities for NMFS Bristol Bay red king crab trawl surveys by Weinberg et al. (2004) and the Bering Sea Fisheries Research Foundation surveys.



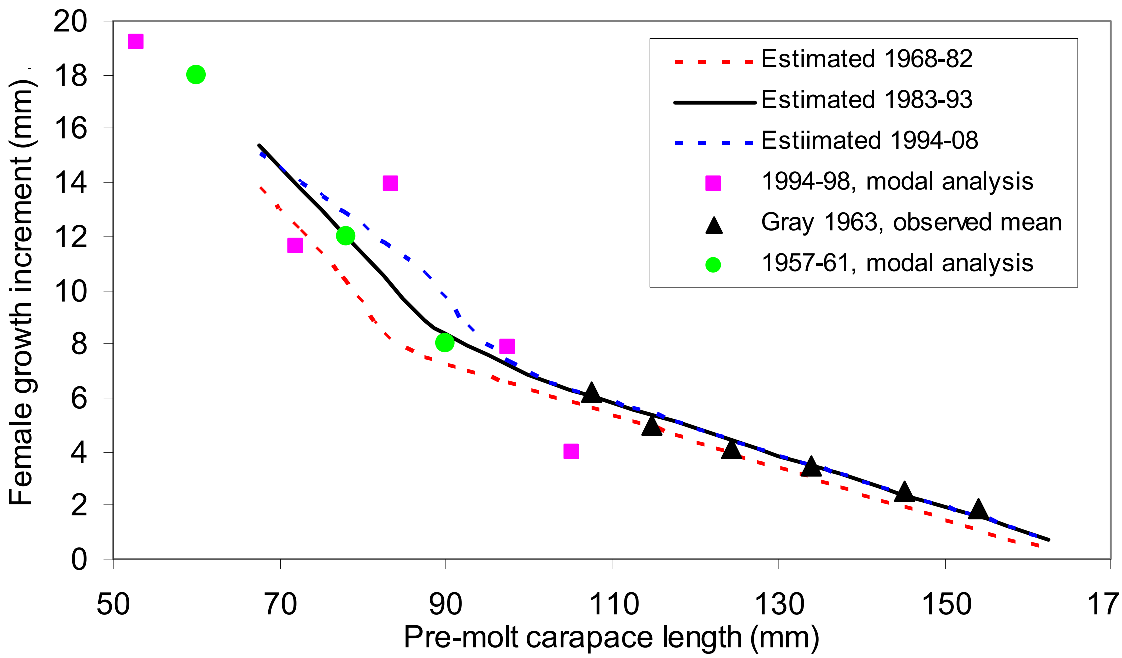


Figure A2. Mean growth increments per molt for Bristol Bay red king crab. Note: "tagging"---based on tagging data; "mode"---based on modal analysis.

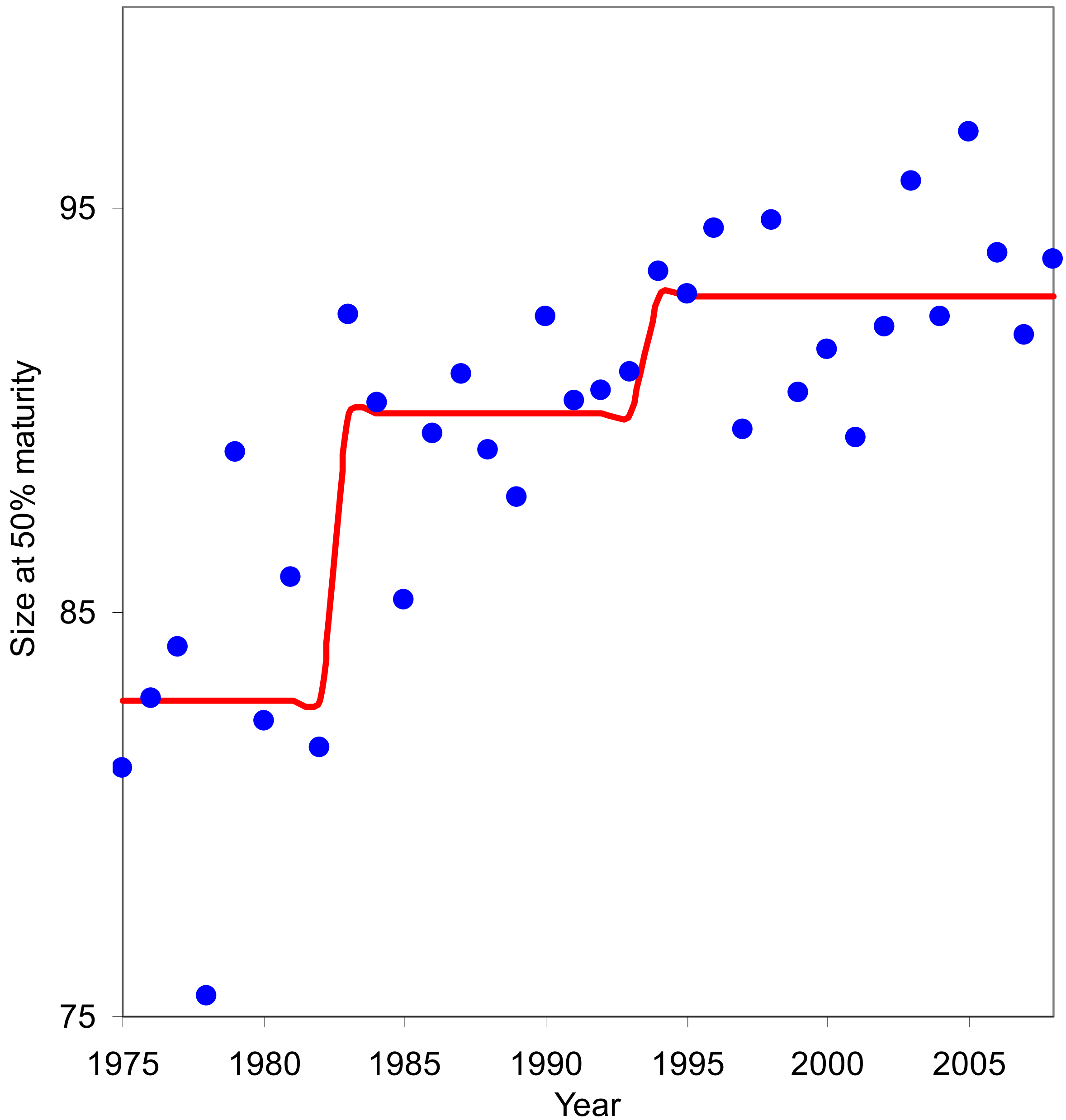


Figure A3. Estimated sizes at 50% maturity for Bristol Bay female red king crab from 1975 to 2008. Averages for three periods (1975-82, 1983-93, and 1994-08) are plotted with a line.

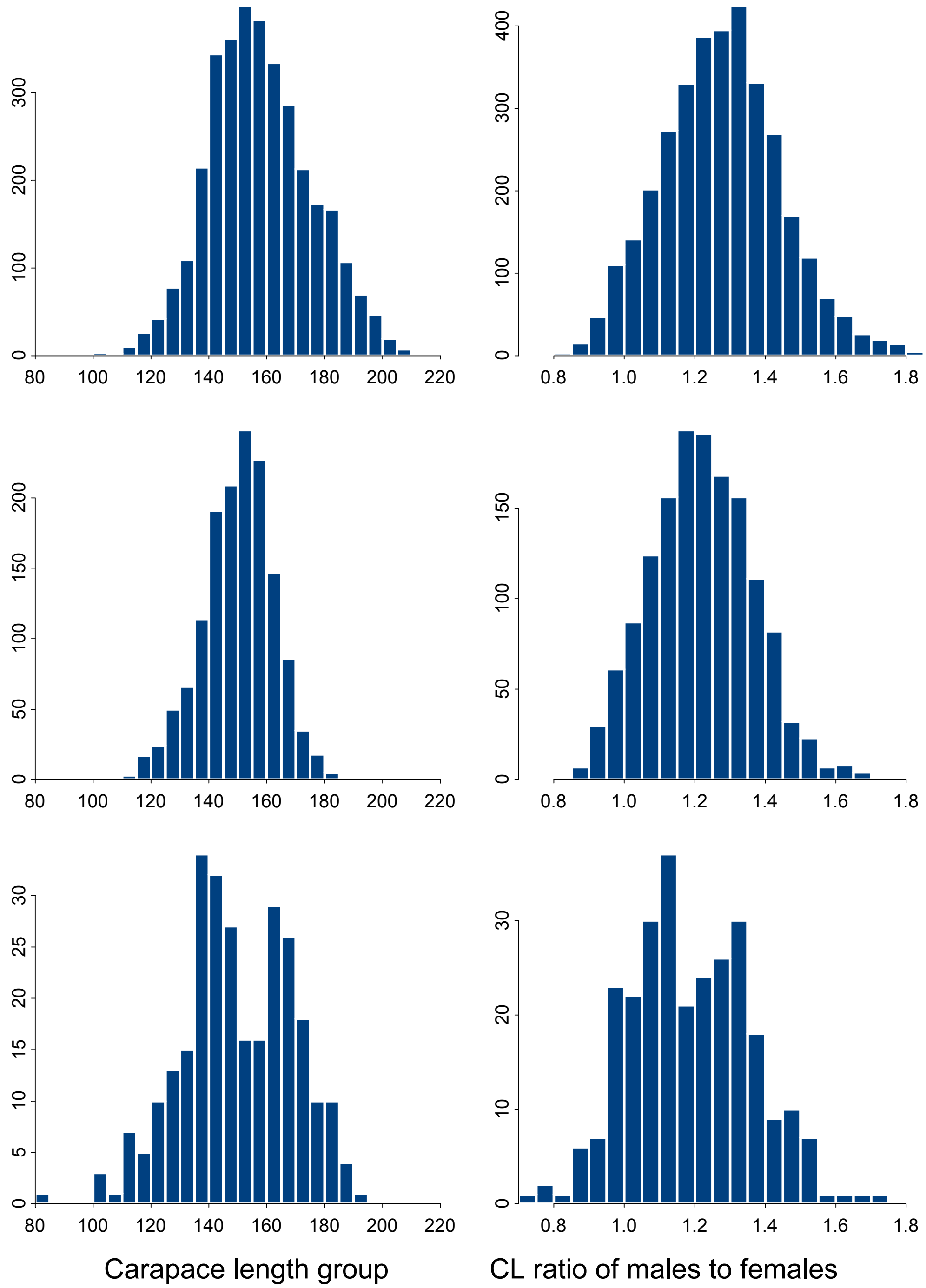
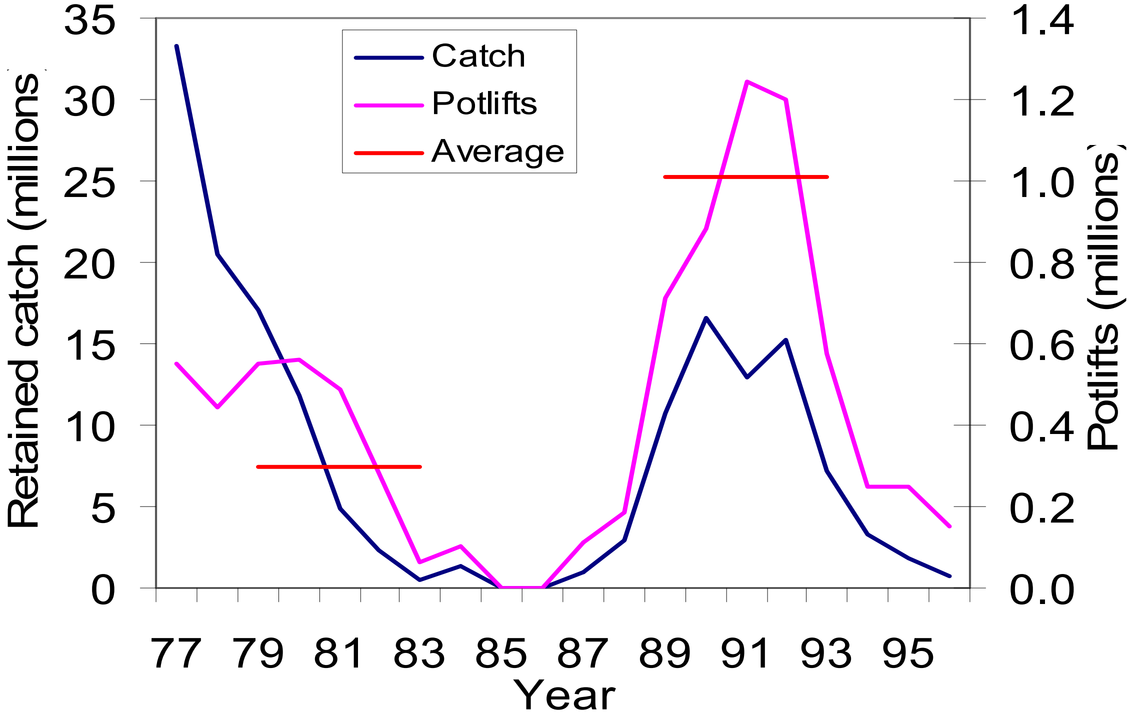


Figure A4. Histograms of carapace lengths (CL) and CL ratios of males to females for male shell ages ≤13 months of red king crab males in grasping pairs; Powell's Kodiak data. Upper plot: all locations and years pooled; middle plot: location 11; lower plot: locations 4 and 13. Sizes at maturity for Kodiak red king crab are about 15 mm larger than those for Bristol Bay red king crab. (Source: Doug Pengilly, ADF&G).



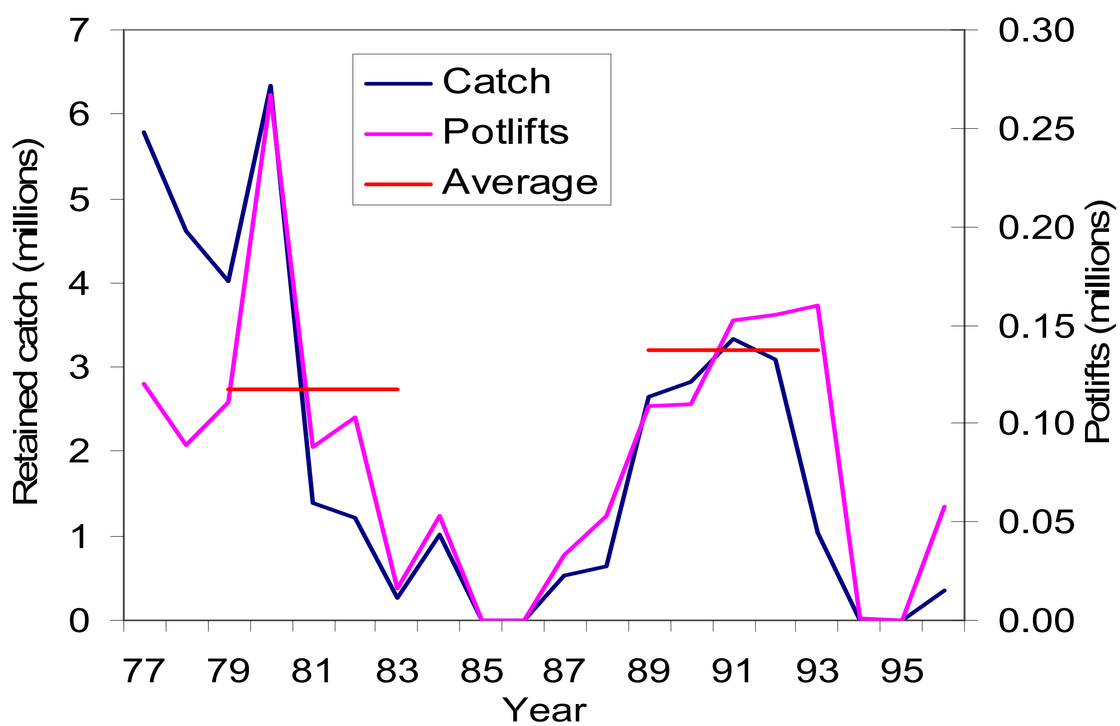
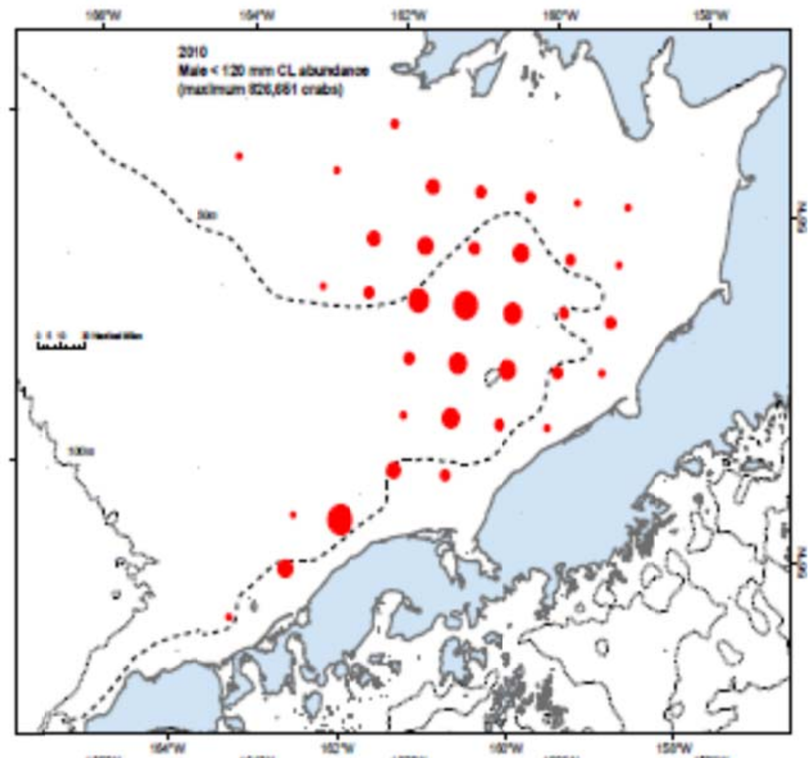
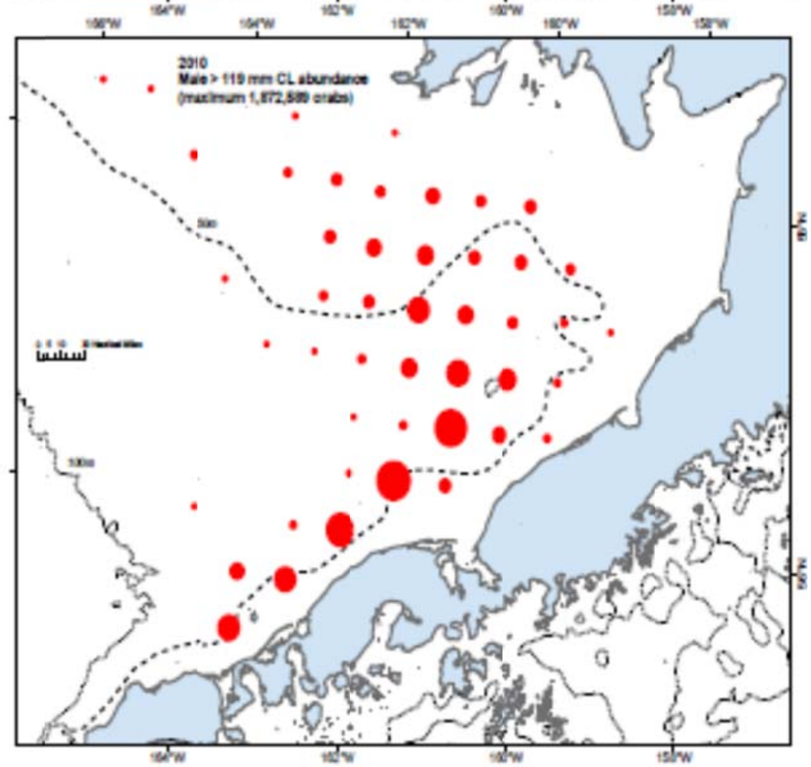
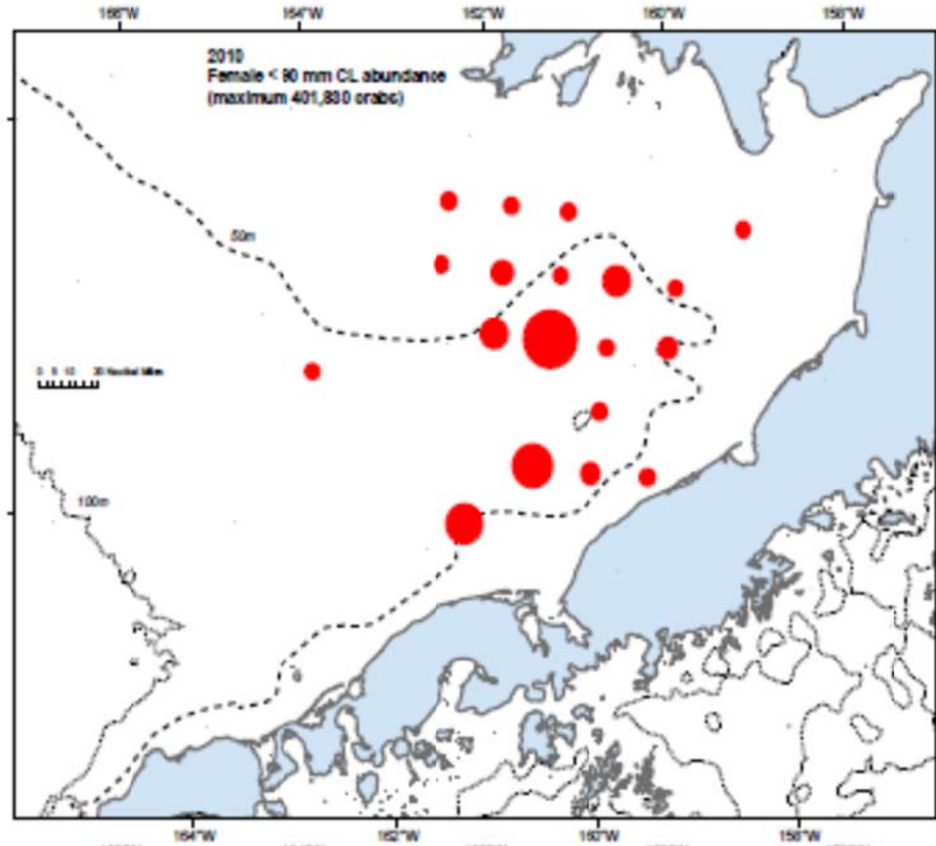


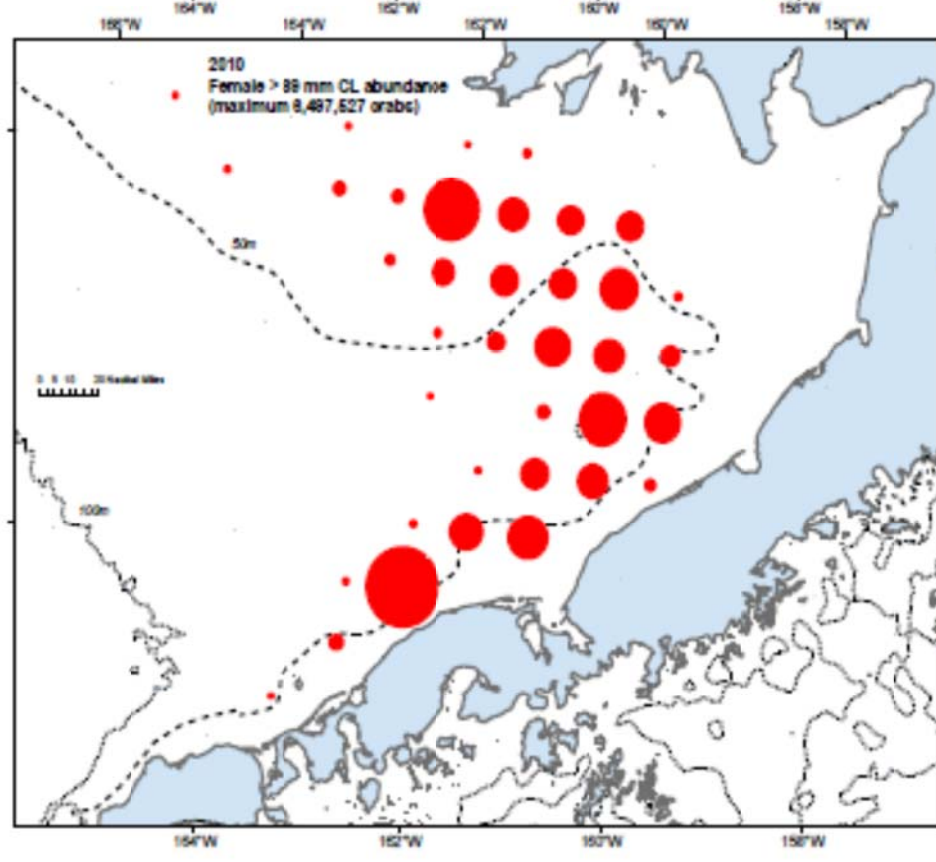
Figure A5. Retained catch and potlifts for total eastern Bering Sea Tanner crab fishery (upper plot) and the Tanner crab fishery east of 163° W (bottom).

Appendix B. Spatial distributions of mature and juvenile male and female red king crabs in Bristol Bay from the 2010 summer trawl survey.






2010
Female < 90 mm CL abundance
(maximum 401,830 crabs)
50m
100m


2010
Female > 89 mm CL abundance
(maximum 8,497,527 crabs)
50m
100m